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FOREWORD

Space Station *Freedom*, now under development, is a manned low Earth orbit facility which will become part of the space infrastructure. Starting in the mid 1990s, *Freedom* will support a wide range of activities, including scientific research, technology development, commercial ventures and, eventually, serve as a transportation node for space exploration. While the initial facility will not be capable of meeting all requirements, the space station will evolve over time as requirements and on-board activities mature and change. The space station design, therefore, allows for evolution to:

- expand capability,
- increase efficiency, and
- add new functions.

It is anticipated that many of the evolutionary changes will be accomplished through on-orbit replacement of systems, subsystems, and components as technology advances. Therefore, technology development is critical to ensure the continuing operation and expansion of the facility.

The Office of Aeronautics, Exploration and Technology (OAET) has sponsored development of many of the technologies that are now part of Space Station *Freedom*'s baseline design. Evolutionary and operational aspects of *Freedom* continue to be an important thrust of OAET's Research and Technology (R&T) efforts.

This workshop has been an important step in our understanding of the space station's baseline systems, the evolutionary scenarios including the station's role in space exploration, and the technologies that will be necessary to meet evolutionary and growth requirements.

It is anticipated that application of the information acquired through the workshop will lead to further technology development efforts to benefit *Freedom* and will lead to continued collaboration between the Space Station *Freedom* Program and the technology development community.

Arnold D. Aldrich
Associate Administrator for Aeronautics, Exploration and Technology

CLARIFICATION

Since the workshop was conducted in January of 1990, there have been some organizational changes throughout the agency. The Office of Aeronautics and Space Technology (OAST) has been reorganized to include the former Office of Exploration and is now called the Office of Aeronautics, Exploration, and Technology (OAET). Also, the Human Exploration Initiative (HEI) has been expanded and renamed the Space Exploration Initiative (SEI). Some of the materials in these proceedings were prepared after the workshop, and, therefore, references to new organizational entities and new programs may be found in certain sections.

TECHNOLOGY FOR SPACE STATION EVOLUTION - A WORKSHOP
Technology Disciplines (STRUCT/MATLS - THERMAL)

VOLUME V

P5

INTRODUCTION

NASA's Office of Aeronautics and Space Technology (OAST) conducted a workshop on technology for space station evolution January 16-19, 1990, in Dallas, Texas. The purpose of this workshop was to collect and clarify Space Station *Freedom* technology requirements for evolution and to describe technologies that can potentially fill those requirements. OAST will use the output of the workshop as input for planning a technology program to serve the needs of space station evolution. The main product of the workshop is a set of program plans and descriptions for individual technology areas. These plans are the cumulative recommendations of the more than 300 participants, which included researchers, technologists, and managers from aerospace industries, universities, and government organizations.

The identification of the technology areas to be included, as well as the development of the program plans, was initiated by assigning NASA chairmen to the eleven technology disciplines under consideration. The disciplines are as follows:

- Attitude Control and Stabilization (ACS)
- Communications and Tracking (C&T)
- Data Management System (DMS)
- Environmental Control and Life Support Systems (ECLSS)
- Extravehicular Activity/Manned Systems (EVA/MANSYS)
- Fluid Management System (FMS)
- Power System (POWER)
- Propulsion (PROP)
- Robotics (ROBOTICS)
- Structures/Materials (STRUCT)
- Thermal Control System (THERM)

Each chairman worked with a panel of experts involved in research and development in the particular discipline. The chairmen, with the assistance of their panels, were responsible for selecting invited presentations, identifying and inviting Space Station *Freedom* Level III subsystem managers, and focusing the discussion of the participants. In each discipline session, presentations describing status of the current programs were made by the Level III subsystem managers and by OAST program managers. After invited presentations by leading industry, university, and NASA researchers, the sessions were devoted to identifying technology requirements and to planning programs for development of the identified technology areas. Particular attention was given to the potential requirements of the Human Exploration Initiative (HEI). The combined inputs of the participants in each session were incorporated into a package including an

overall discipline summary, recommendations and issues, and proposed development plans for specific technology areas within the discipline. These technology discipline summary packages were later supplemented by the chairmen and their panels to include the impact of varied funding levels on the maturity of the selected technologies. OAST will review the program plans and recommended funding levels based on available funding and overall NASA priorities and incorporate them into a new OAST initiative advocacy package for space station evolution technology.

These proceedings are organized into an Executive Summary and Overview and five volumes containing the Technology Discipline Presentations.

Volume V consists of the technology discipline sections for Structures/Materials and the Thermal Control System. For each technology discipline in this volume, there is a Level 3 subsystem description, along with the invited papers for that discipline.

Structures/Materials

Level III

Subsystem Presentation

N93-27836

STRUCTURES FOR SPACE STATION FREEDOM

OVERVIEW OF CURRENT CONCEPT

NASA/JSC
DR. KORNEL NAGY
713-483-8830

AGENDA

INTRODUCTION

STRUCTURES SUBSYSTEM

MECHANICAL SUBSYSTEM

EVOLUTION ISSUES

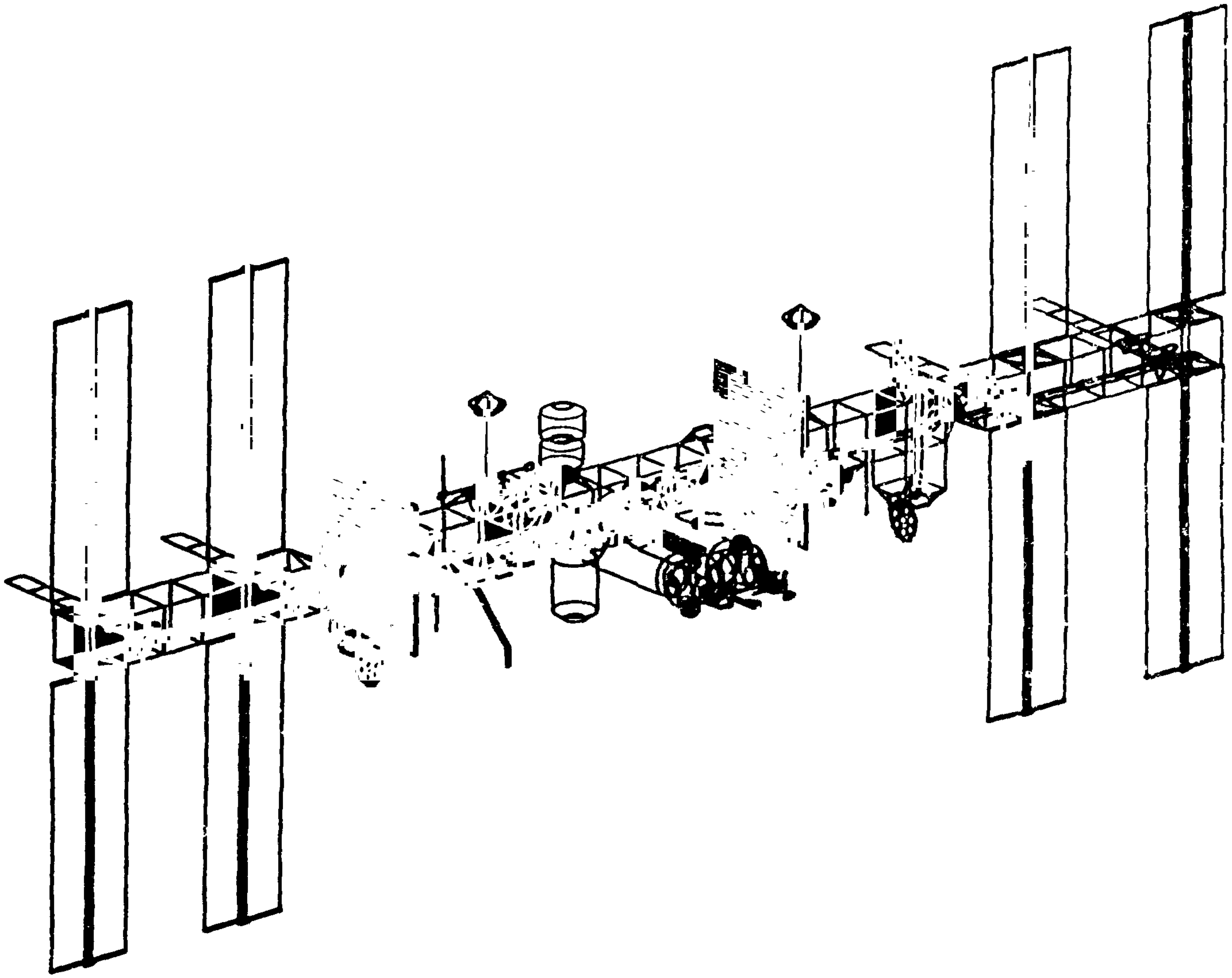
INTRODUCTION

- SSF IS FIRST SPACECRAFT ASSEMBLED ON-ORBIT
- STRUCTURAL CONCEPT DEVELOPED TO ACCOMMODATE PHASED ASSEMBLY
  - CONCEPT ORIGINATED AT LARC
  - FINAL DESIGN UNDERWAY
- STRUCTURES DEVELOPMENT TO ENABLE POSSIBLE STATION GROWTH OPTIONS
  - POWER SYSTEM GROWTH
  - CONSTRUCTION ACTIVITIES
  - LUNAR/MARS INITIATIVE

STRUCTURES SUBSYSTEM

The WP-02 Assembly Truss and Structures subsystem includes the Assembly Truss, Mobile Transporter, Airlock, and Resource Node structure. The Station Assembly Truss includes all truss structures resource pallets, component supports, and module to truss interface structure. The turntable, hinge, and track assemblies, and the upper and lower base are WP-02 structural components of the Mobile Transporter. Within the Airlock, WP-02 structural responsiblity includes airlock primary structure, secondary structures, micro-meteoroid and debris shields, NSTS attachment equipment, and grapple fixtures. The Resource Node structural subsystem contains the primary and secondary structures, micro-meteoroid/debris shields, NSTS grapple and attachment fixtures, and the cupola (MSFC supplied).

STRUCTURES / MATERIALS



ASSEMBLY TRUSS/STRUCTURES

- ASSEMBLY TRUSS STRUCTURES --TRUSS STRUCTURES,COMPONENT SUPPORT/ADAPTORS RESOURCE PALLETS,MODULE TO TRUSS INTERFACE STRUCTURE,UTILITY TRAYS
- MOBILE TRANSPORTER STRUCTURE-- UPPER BASE,TURNTABLE ASSEMBLY,TRACK ASSEMBLY,HINGE ASSEMBLY,LOWER BASE
- AIRLOCK STRUCTURE-- PRIMARY STRUCTURE,SECONDARY STRUCTURE, METEROID DEBRIS SHIELD,NSTS ATTACHMENT FIXTURES AND GRAPPLE FIXTURES
- RESOURCE NODE STRUCTURE-- PRIMARY AND SECONDARY STRUCTURE, METEROID/DEBRIS SHIELD,NSTS ATTACHMENT AND GRAPPLE,CUPOLA
- HAB AND LAB MODULE STRUCTURE-- PRIMARY AND SECONDARY STRUCTURE METEROID/DEBRIS SHIELD, NSTS ATTACHMENT AND GRAPPLE

Requirements for the Station structure are meant to insure the integrity of the configuration, the accomplishment of mission goals, and the safety of the crew. To this end, the structure must be able to provide support for all equipment attached to the Space Station, both payloads and other Station subsystems. The primary truss structure must provide adequate stiffness such that Station maneuvering (i.e. docking, reboost, attitude control, etc.) can be accomplished with adequate control system stability margins. The overall stiffness and thermal stability of the structure must also contribute to achieving the pointing requirements for the antennas and payloads. The Space Station Freedom is designed for a 30 year on-orbit life. The structural subsystem must meet the structural requirements for the entire design life of the Station. Therefore, structural components must be resistant to the degrading effects of the space environment (i.e. radiation) and tolerant to damage inflicted by space borne particles (i.e. micro-meteoroid and debris).

FUNCTIONAL AND PERFORMANCE REQUIREMENTS

- STRUCTURAL SUPPORT FOR ALL SUBSYSTEMS (MODULES, POWER, THERMAL, FLUIDS...)
- ACCOMMODATE PAYLOADS, PROPULSION MODULES, UNIVERSAL PALLETS...
- ADEQUATE STIFFNESS FOR STATION MANEUVERING (DOCKING, REBOOST, ATTITUDE CONTROL)
- SUPPORT PAYLOAD AND ANTENNA POINTING REQUIREMENTS
- 30 YEAR LIFE
- DAMAGE TOLERANCE
- MINIMUM WEIGHT

Space Station Freedom is designed to be assembled in Earth orbit from resources delivered by the NSTS. Structural designs must account for the assembly process that includes the NSTS payload bay for manifesting, the Remote Manipulator System (RMS) for grappling, holding, and positioning, and special considerations for the EVA crewman.

In addition to the above requirements, special consideration is given to pressurized vessels on the Space Station. The stored energy in these vessels presents a potential hazard to the Station and crew (particularly EVA crew). These systems are designed to "leak before rupture" requirements. Further, other Station structure (and systems) must consider the effects of pressurized vessel explosive failure in their design.

FUNCTIONAL AND PERFORMANCE REQUIREMENTS

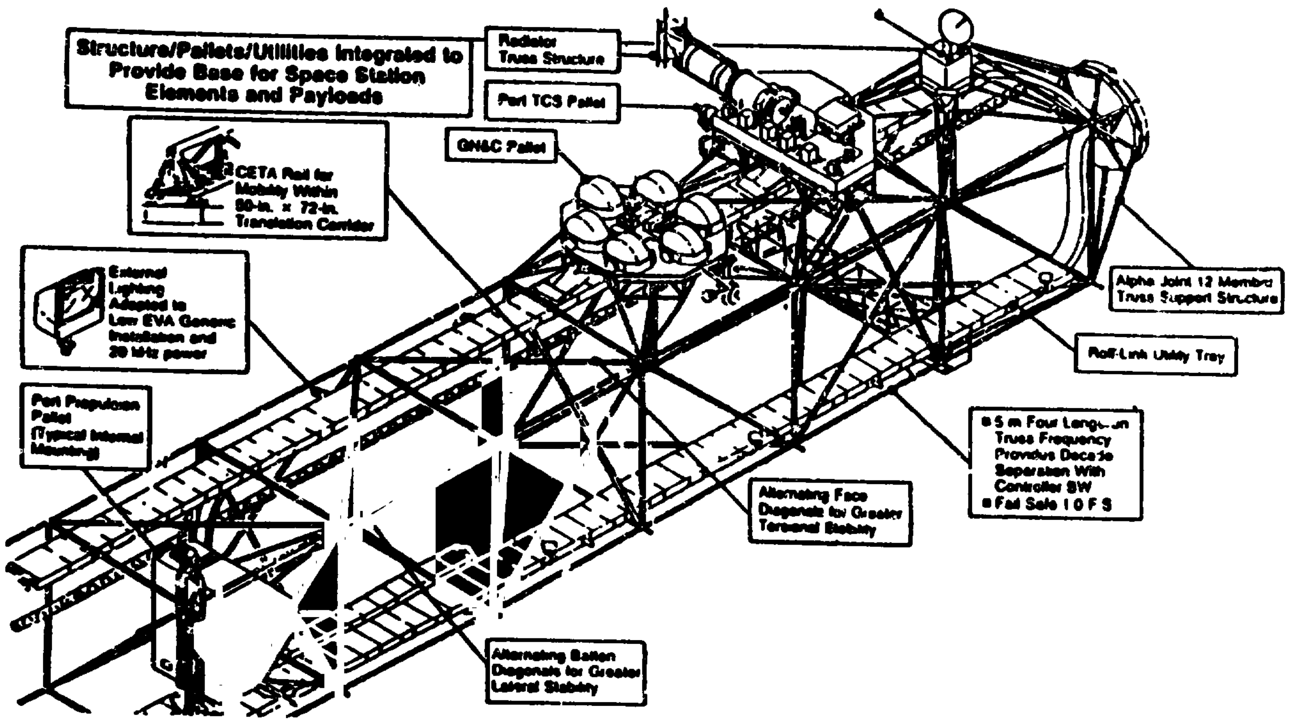
- ON-ORBIT ASSEMBLY OF STRUCTURE

  LAUNCH COMPONENTS STOWED IN CARGO BAY

  SEQUENCED ASSEMBLY OF STRUCTURE AND SUBSYSTEMS

  LIMITED AVAILABILITY OF EVA

STRUCTURES / MATERIALS



PORTION OF TRUSS WITH SUBSYSTEMS

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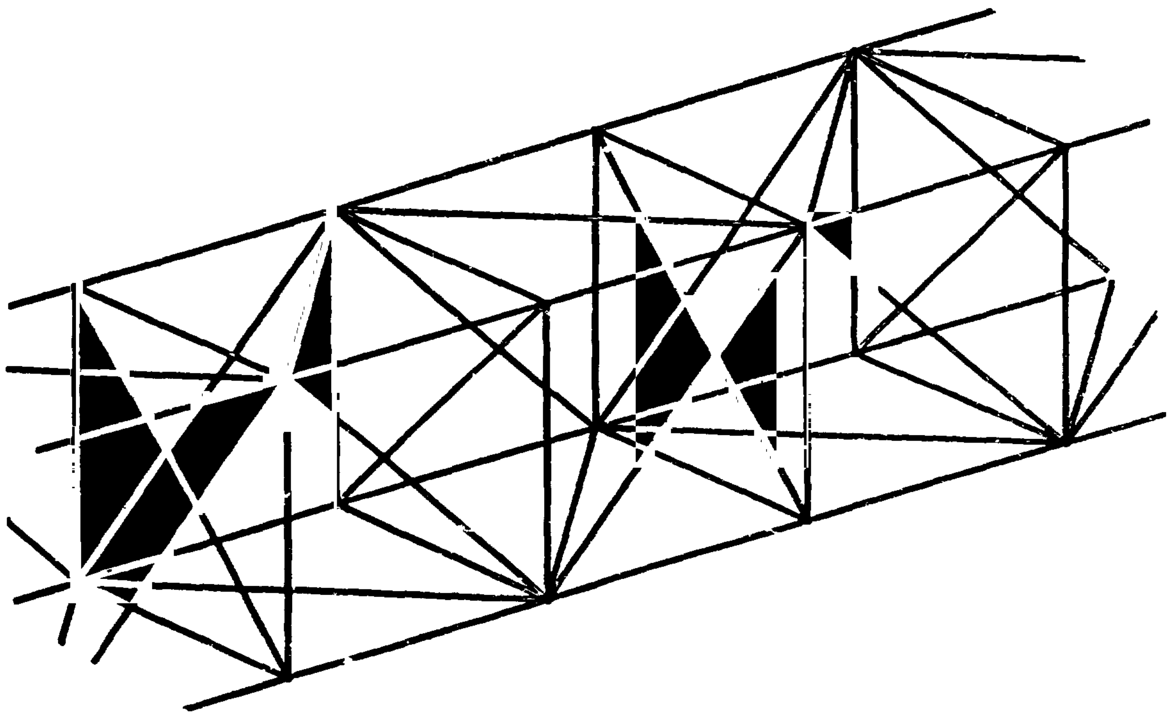
The primary truss structure consists of a 5 meter cubical cell composed of graphite/epoxy struts. The strut outside diameter has been sized to 2 inches to accommodate the grip of the EVA crewman. The truss struts have specially designed end fittings that enable complete truss construction by EVA. The truss was sized at 5 meters to provide stiffness margin for the control system. Also, the 5 meter truss provides an internal cross-section equivalent to the Orbiter payload bay.

DESIGN IMPLEMENTATION

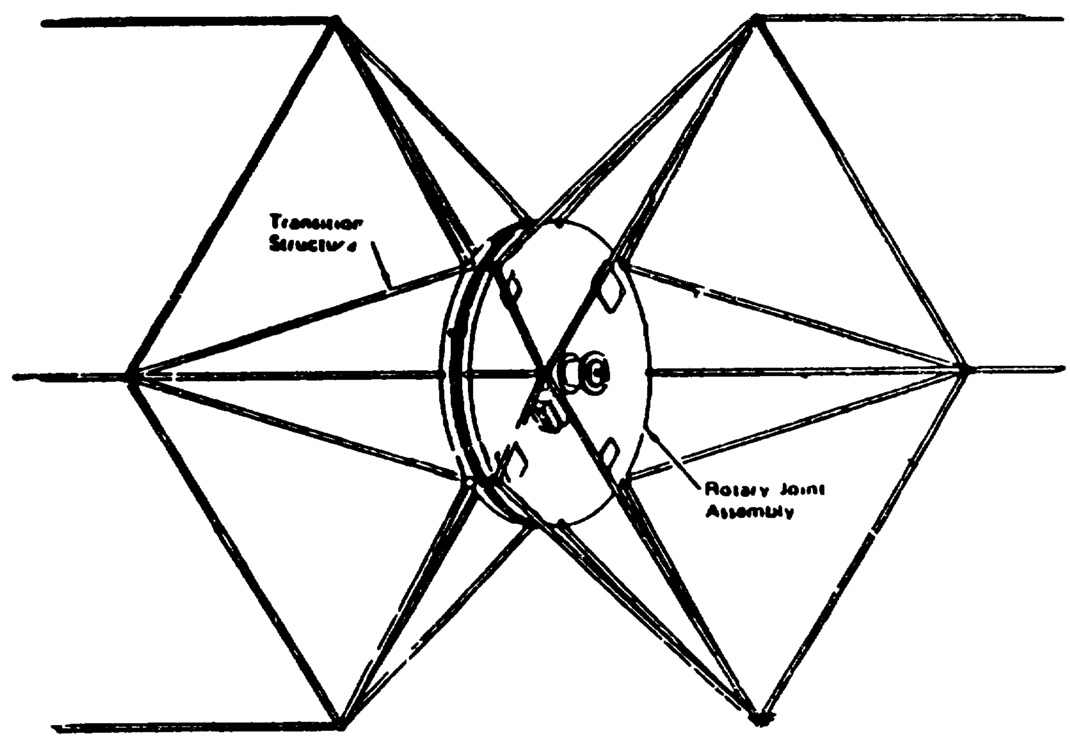
- PRIMARY TRUSS
  - 5 METER CUBICAL CELL SIZE
  - EVA ERECTABLE
  - GRAPHITE /EPOXY TRUSS TUBES
- MODULE TO TRUSS INTERFACE STRUCTURE
  - DEPLOYABLE TRUSS
- UNIVERSAL PALLETS
  - LIGHTWEIGHT PALLET DESIGN
  - FOLD-OUT STRUTS FOR STATION ATTACH OF PALLETS
  - DUAL USE PALLETS, STATION AND ORBITER PAYLOAD BAY

STRUCTURES / MATERIALS



5 METER PRIMARY TRUSS

STRUCTURES / MATERIALS



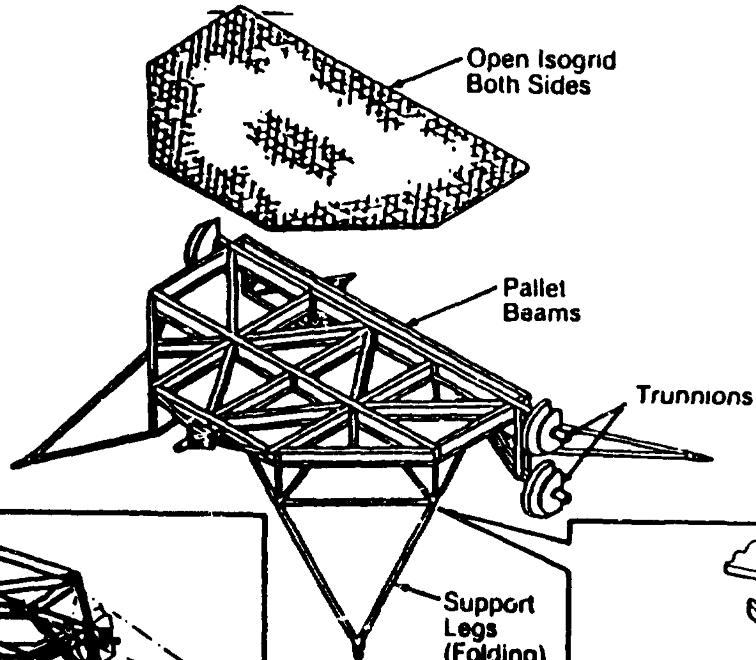
ALP.IA JOINT WITH TRANSITION STRUCTURE

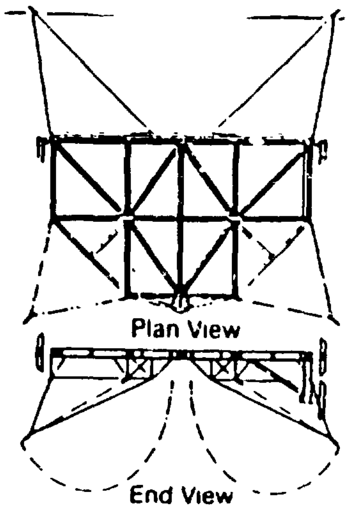
The resource pallets are a light weight aluminum design that supports subsystem components during launch. When connected to the Space Station, these pallets become the hardware platform that structurally integrates the subsystems into the Space Station. The resource pallet design allows for truss and utility connections to be common for all subsystems supported by a pallet.

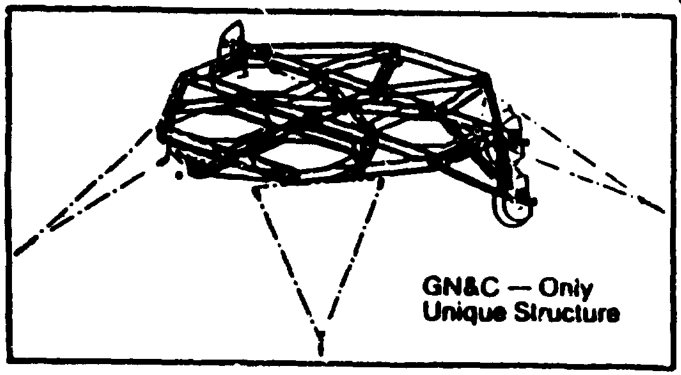
STRUCTURES / MATERIALS

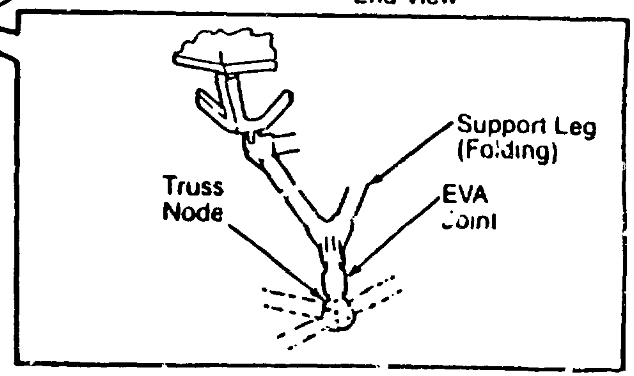
Features
■ Uses Standard EVA Joints ■ Folding Support Legs for: • Thermal Compensation • Packaging Density ■ Ground Installation and C/O ■ Universal Isogrid Attach Pattern ■ Minimizes DDT&E Costs

.'allet Structural Weights
11 Units



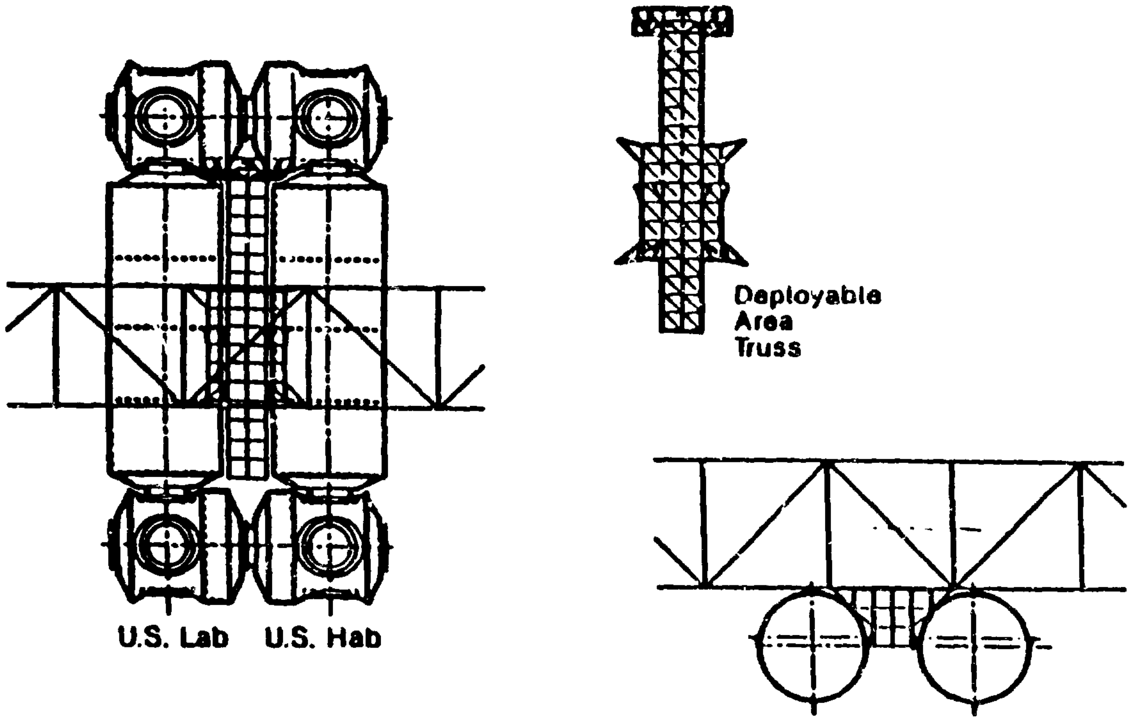






UNIVERSAL PALLET

STRUCTURES / MATERIALS



MODULE TO TRUSS INTERFACE STRUCTURE

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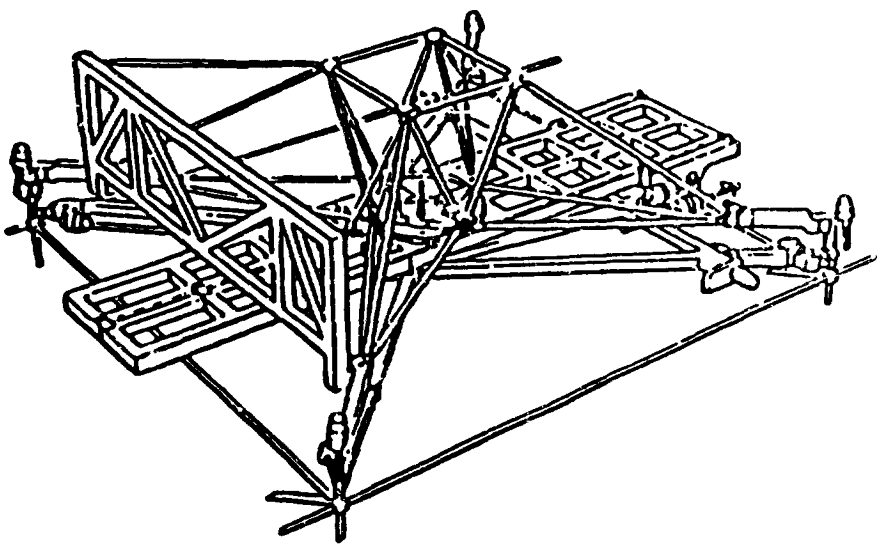
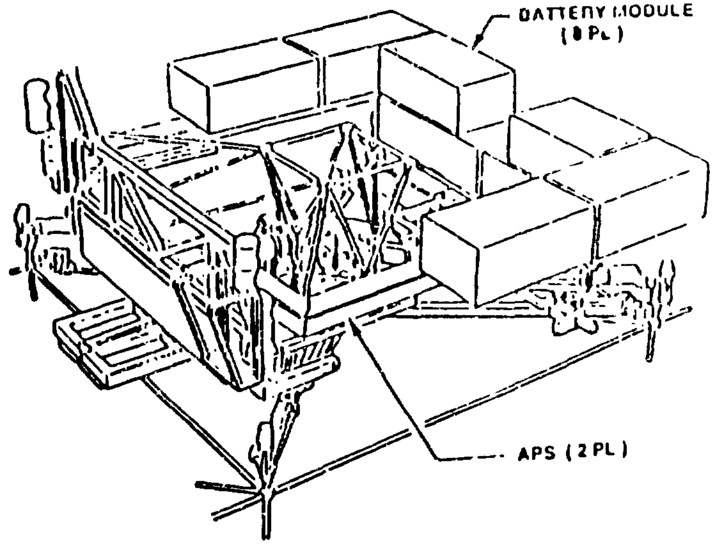
The mobile transporter base assembly consists of an upper and lower layer that can slide relative to each other. Sliding one layer forward (or backward) to pick up the nodes of the next bay of truss is the method by which the transporter move along the truss. A additional degree of freedom is achieved by a central turntable system that allows the transporter to rotate, while still attached to the truss, about an axis perpendicular to the truss face attached to the base.

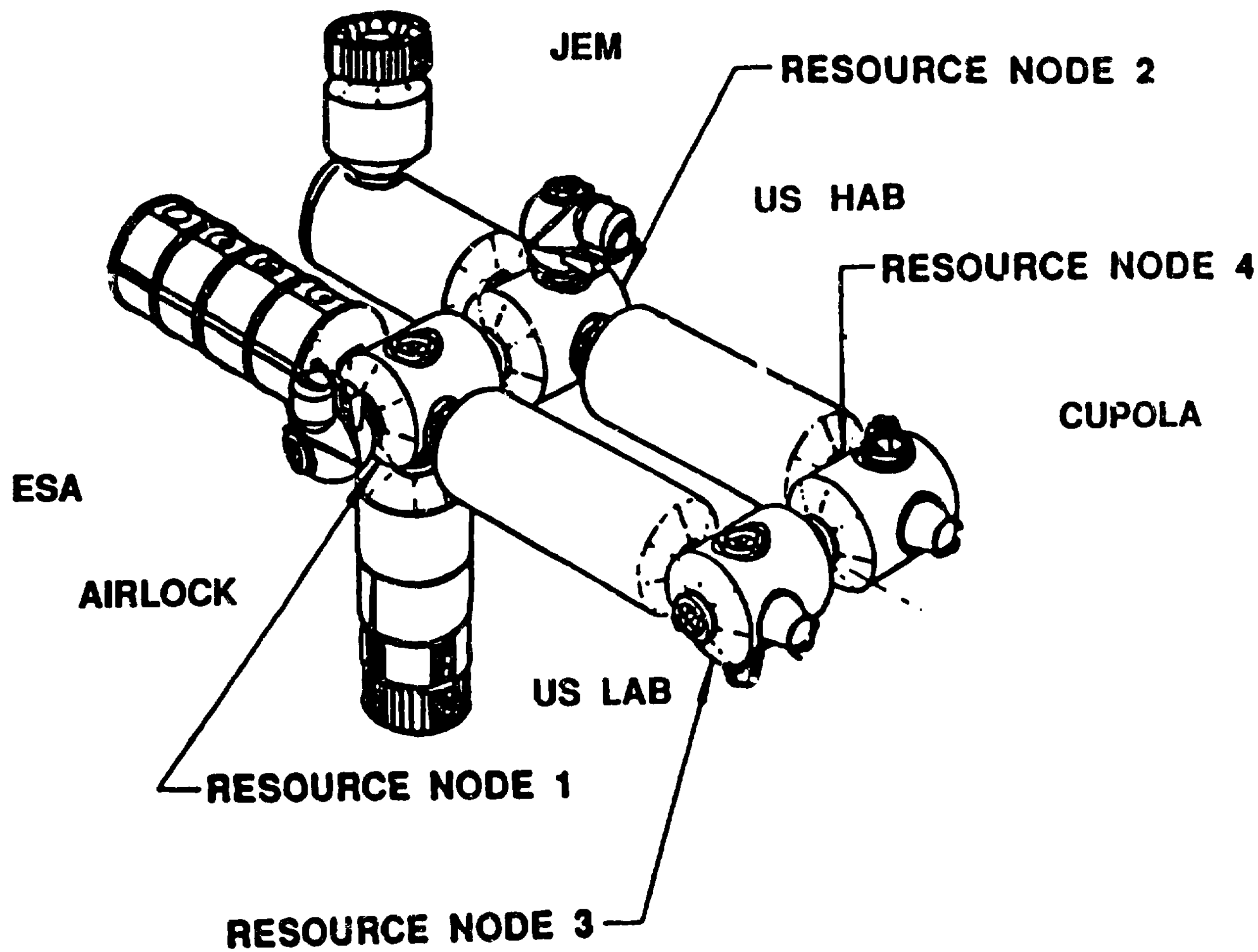
STRUCTURES / MATERIALS

MOBILE TRANSPORTER





STRUCTURES / MATERIALS



MODULE PATTERN

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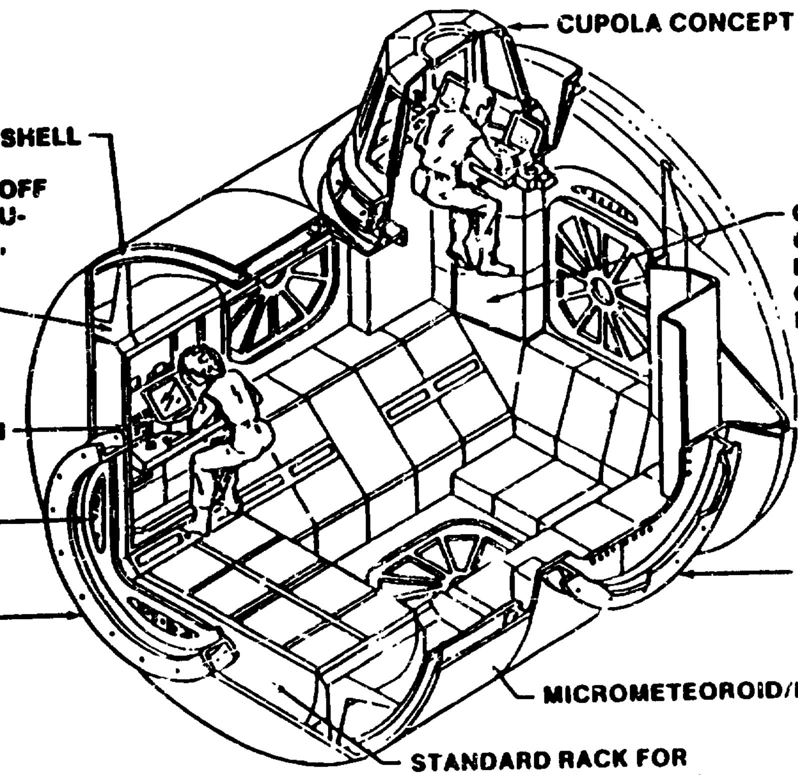
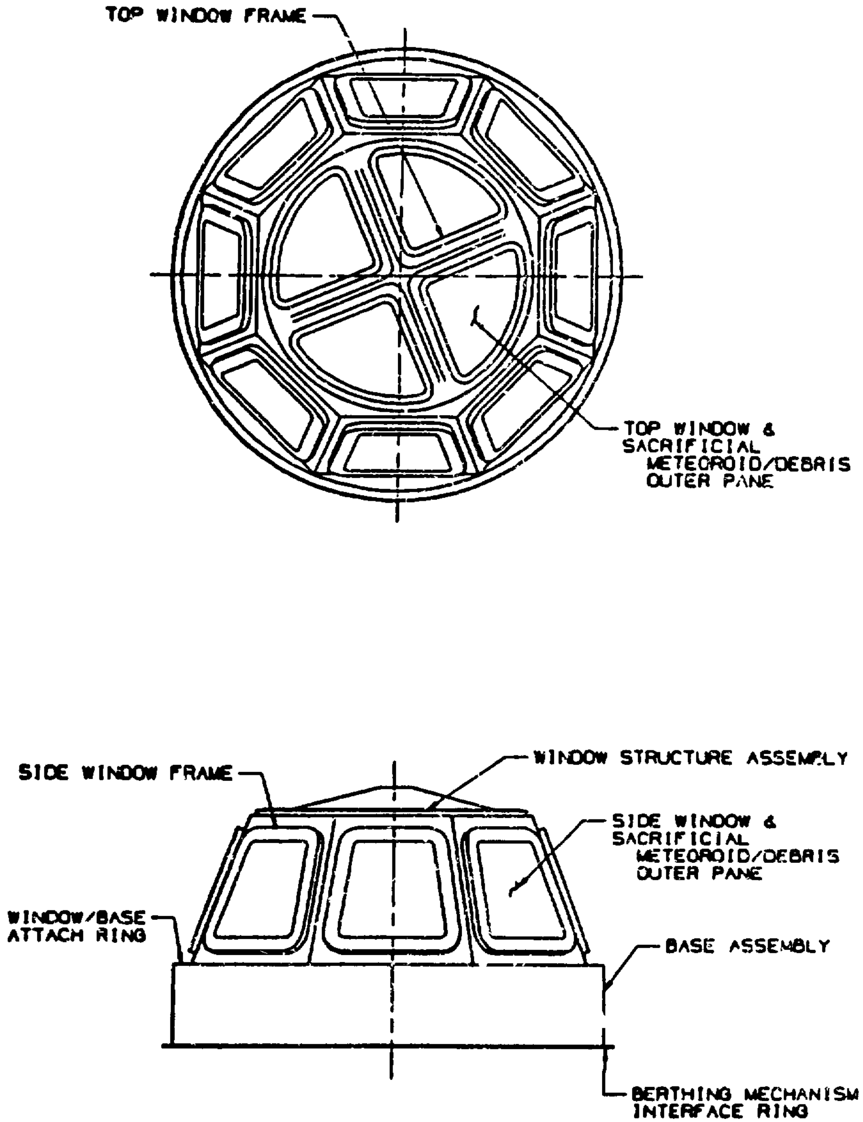
Sharing common structural concepts with the other Station modules, the resource node assembly provides additional volume to locate Station subsystems and equipment. Micro-meteoroid and debris shielding is incorporated into the outer shell to provide protection for the crew. Attached to one of the resource nodes is an airlock with one atmosphere and hyperbaric (six atmospheres) capability.

STRUCTURES / MATERIALS



RESOURCE NODE

STRUCTURES / MATERIALS



CUPOLA

Assembling the Space Station requires hardware developed and built at one work package to be integrated into hardware produced at another work package. The WP-02 development of the module to truss interface structure will be integrated into the module design of WP-01. Similarly, transition hardware that connects the WP-04 alpha joint to the WP-02 truss must be developed from controlled interfaces. WP-03 and WP-02 require agreements for the proper design of hardware that integrates attached payloads to the truss structure. The development of the transporter base (upper and lower) must be coordinated with Canada to insure the proper operation of the top level assembly. Ultimately, each subsystem or Station component must integrate to the primary truss structure for on-orbit support.

KEY TECHNICAL CHALLENGES	APPROACH TO CHALLENGES
• 30 YEAR CERTIFICATION OF NON-METALLIC STRUCTURES TRUSS MOBILE TRANSPORTER	• ATOMIC OXYGEN FLIGHT EXPERIMENT • DEGRADATION STUDIES/COATINGS • MATERIAL PROPERTIES DATA BASE DEVELOPMENT
• METEROID AND DEBRIS PROTECTION FOR STATION COMPONENTS	• LIGHT WEIGHT SHIELDING CONCEPTS • ADD-ON PROTECTION (10 YEAR INCREMENTS)
• ON-ORBIT ASSEMBLY	• GROUND TESTS • POTENTIAL FLIGHT TESTS (CETA RAIL)
• DEVELOPMENT AND CERTIFICATION OF HIGH PRESSURE TANKS	• ON-GOING DEVELOPMENT OF DATA BASE

INTERFACES WITH OTHER SUBSYSTEMS/ELEMENTS

- THE PRESSURIZED MODULES ATTACH TO THE TRUSS AT THE CENTER OF STATION MODULE TO TRUSS INTERFACE STRUCTURE
- THE PALLETS ARE THE MEANS OF MOUNTING SUBSYSTEMS ON THE TRUSS
- THE CABLE TRAYS AND CETA RAIL ARE MOUNTED ON THE TRUSS BATTENS
- THE ALPHA ROTARY JOINT IS ATTACHED THE TRUSS WITH UNIQUE SET OF STRUTS
- THE PRESSURIZED COMPONENTS ARE MATED WITH COMMON BERTHING MECHANISMS (INCLUDING THE INTERNATIONAL PARTNERS)
- THE CANADIAN MSC IS ATTACHED TO THE MOBILE TRANSPORTER

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ACCOMPLISHMENTS TO DATE

- PROTOTYPE HARDWARE FOR 5 METER TRUSS BUILT AND TESTED
  - EXTENSIVE WETF TESTING OF TRUSS COMPONENTS
  - TRUSS TUBE VENDOR SELECTED
- MODULE TO TRUSS INTERFACE STRUCTURE CONCEPT UNDER REVIEW
- COMPLETED INITIAL LOAD ANALYSIS (INCLUDES DOCKING AND PLUME IMPINGEMENT)
- PRELIMINARY DESIGN IN WORK FOR PRESSURIZED STRUCTURES
  - AIRLOCK
  - NODES
  - CUPOLA
  - MODULES

MECHANICAL SUBSYSTEM

MECHANICAL SYSTEMS DESCRIPTION

1. ORBITER TO STATION ATTACHMENT (DOCKING MAST) PROVIDES RIGID STRUCTURAL CONNECTION WHILE MAINTAINING PRESSURIZED CREW AND SELECTED EQUIPMENT TRANSFER
   - IN ORDER TO ENHANCE ORBITER DELIVERY CAPABILITY, MOST OF ATTACHMENT IS LOCATED ON STATION
2. UNPRESSURIZED BERTHING SYSTEM ATTACHES LOGISTIC MODULES TO TRUSS AT 3-POINTS USING LONG ALIGNMENT GUIDE LATCHES
3. SOLAR ALPHA ROTARY JOINTS PROVIDE POINTING CORRECTIONS FOR ELECTRICAL POWER SYSTEM WHILE TRANSFERRING POWER AND DATA
4. THERMAL RADIATOR ROTARY JOINTS POINT CENTRAL RADIATOR PANELS WHILE TRANSFERRING FLUIDS, POWER AND DATA
5. MOBILE TRANSPORTER PROVIDES TRANSLATION, ROTATION AND PLANE CHANGE MOBILITY FOR CANADIAN MOBILE REMOTE SERVICER

MECHANICAL SYSTEMS DESCRIPTION (concluded)

6. DEPLOYABLE ASSEMBLY WORK PLATFORM WITH ASTRONAUT POSITIONING (3-DOF) SYSTEM MOUNTED ON MT TO PROVIDE CAPABILITY FOR TWO CREW MEMBERS TO ASSEMBLE STATION TRUSS FROM CARGO BAY OF ORBITER

   - UNPRESSURIZED DOCKING SYSTEM ON PLATFORM TO SUPPORT ORBITER TO STATION ATTACHMENT FOR STATION ASSEMBLY AND CREW TRANSFER VIA EVA

7. UTILITY SPOOL PROVIDES STS PACKAGING, SUPPORT, AND RESTRAINT DURING LAUNCH AND ON-ORBIT DEPLOYMENT DURING TRUSS ASSEMBLY

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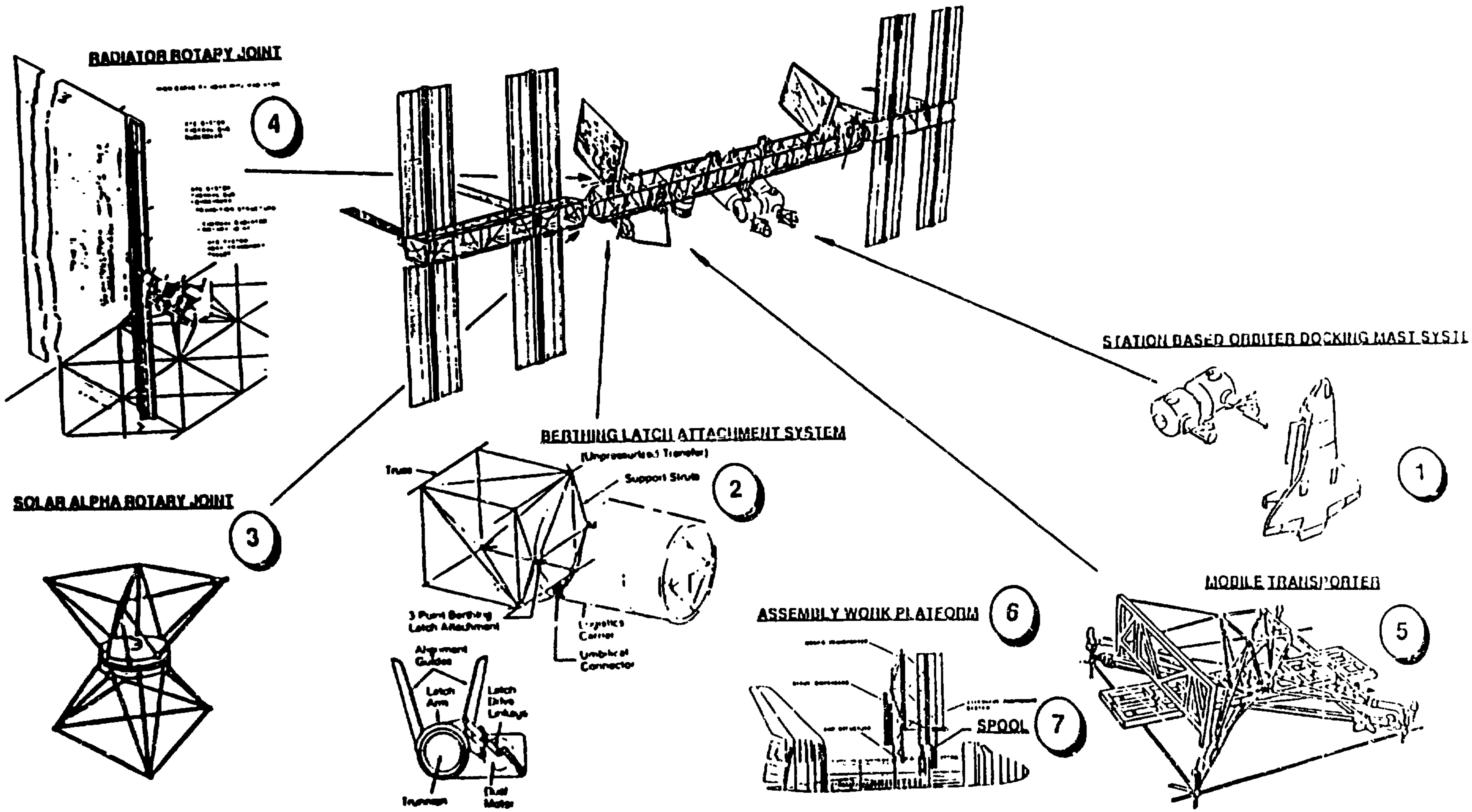
MECHANICAL SYSTEMS



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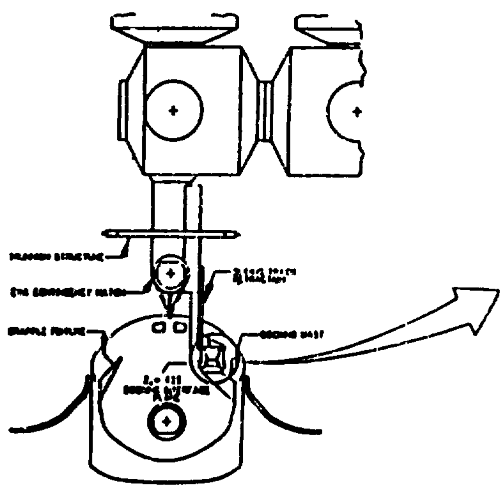
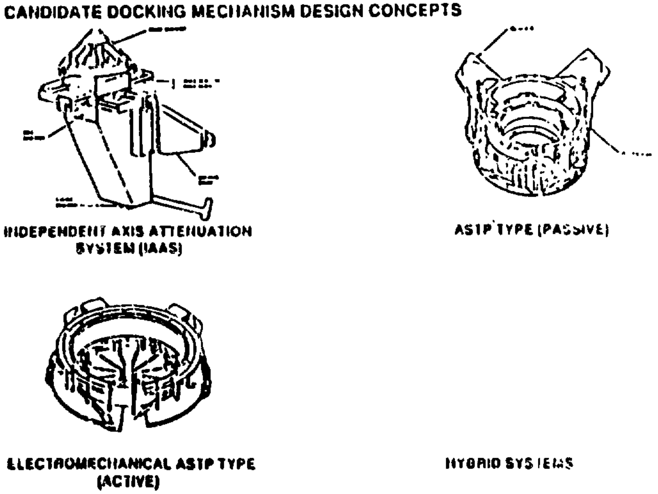
MECHANICAL SYSTEMS MAJOR TRADES

- ACTIVE ELECTROMECHANICAL ACTUATOR DEMONSTRATED BY MDAC ADVANCED DEVELOPMENT HARDWARE
- ORBITER TO STATION DOCKING MAST SYSTEM CONCEIVED BY JSC
- DOCKING MAST CONCEPT USING ACTIVE ELECTROMECHANICAL ACTUATOR PROBE/DROGUE SYSTEM CONCEIVED BY MDAC
- DOCKING MAST CONCEPT USING PASSIVE INDEPENDENT AXIS ATTENUATION SYSTEM CONCEIVED BY ROCKWELL INTERNATIONAL



o CANDIDATE DOCKING MECHANISM DESIGN CONCEPTS



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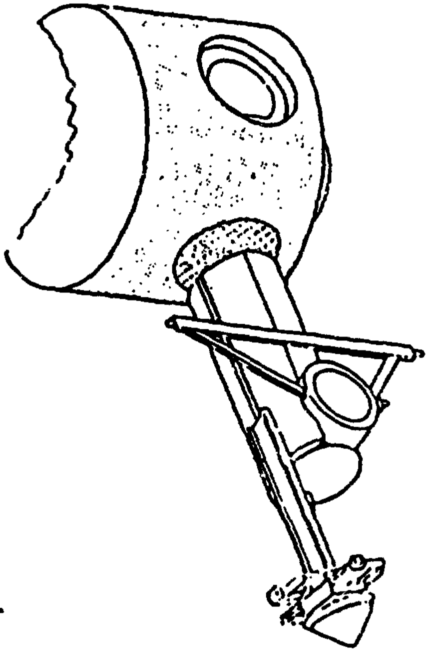
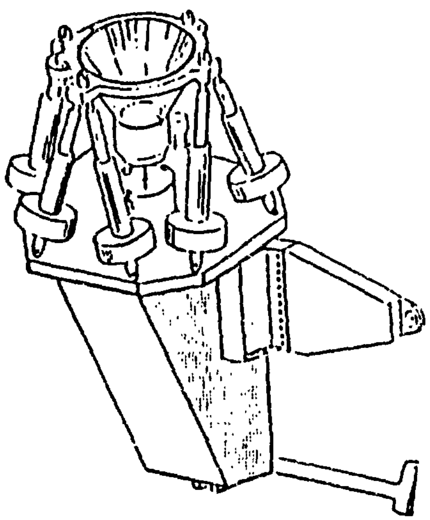
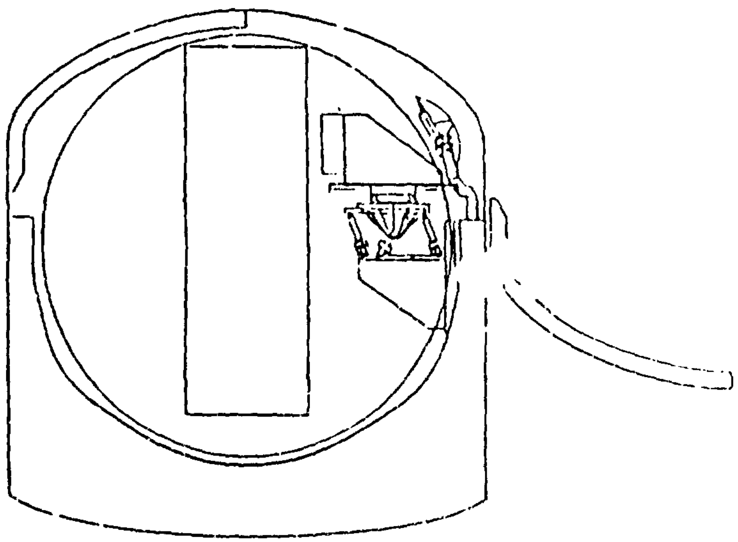
THE DOCKING MECHANISM

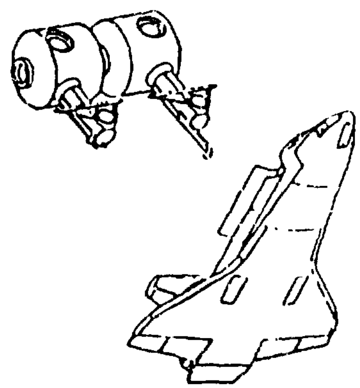






DOCKING MECHANISM MOUNTED
IN THE ORBITER (FIRST LAUNCH CONFIG)

- <u>DOCKING AND BERTHING</u>
    - DOCKING MAST MOCK-UP TESTS IN THE ORBITER FULL FUSELAGE TRAINER (BUILDING 9A/ JSC)
        - DESIGN, FABRICATION, INSTALLATION AND CHECK OUT HAVE BEEN COMPLETED.
    - ES/ROCKWELL DOCKING INTERFACE MECHANISM STUDY
        - ES6 TASKED TO FORM A TEAM TO EVALUATE THE DOCKING MAST MECHANISM CONCEPTS AND SELECT THE SYSTEM BEST SUITED FOR DOCKING AND BERTHING. COMPLETED ACTIVITY IN MID APRIL 1989.
    - TESTING OF MDAC ADVANCED DEVELOPMENT HARDWARE ON 6 DOF DYNAMICS SIMULATOR (BUILDING 13/ JSC)
        - DESIGN AND FABRICATION COMPLETED



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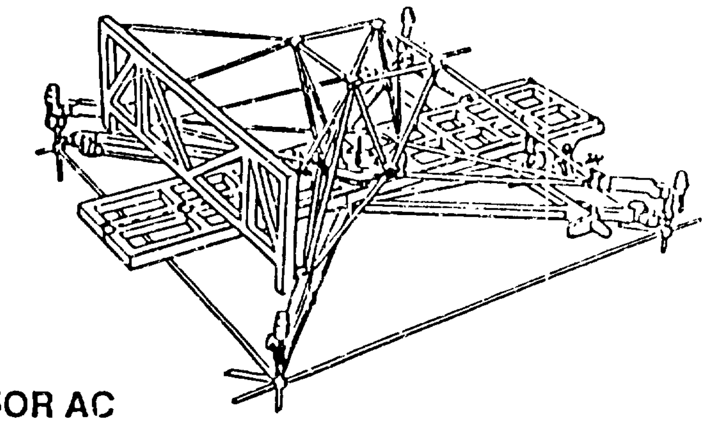
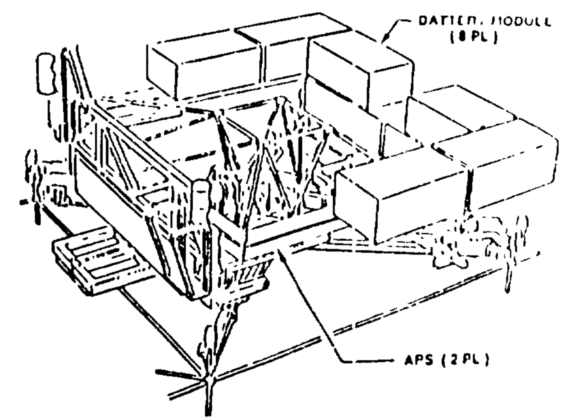
• MOBILE TRANSPORTER



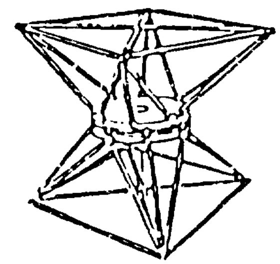


- REVISED REQUIREMENTS
  - AUTONOMOUS MT DELETED
  - RF TO MT/MRS DELETED
  - PLANE CHANGE SCARRED FOR PMC / REQUIRED FOR AC
- CONTRACTOR PLANNING TO RETAIN PLANE CHANGE FOR PMC
- MT/MRS STRUCTURAL INTERFACE CONCEPT DEFINED
  - PROGRAMATIC RESPONSIBILITIES IN WORK
- STOWAGE ENVELOPES FOR APS AND BATTERIES ESTABLISHED

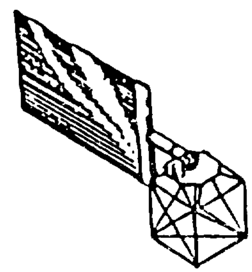
- ROTARY JOINTS (SARJ & TRRJ)
  - PRELIMINARY DESIGN
  - SUBCONTRACT PREPARATIONS & NEGOTIATIONS
  - PDR PREPARATIONS
  - DEFINE SOFTWARE FUNCTIONAL REQUIREMENTS
  - DEFINE SIMULATION SOFTWARE
  - DESIGN SPECIAL TEST EQUIPMENT

- SOLAR ALPHA ROTARY JOINT (SARJ) ACTIVITIES
  - ELECTRONIC CONTROLS PRELIMINARY DESIGN
  - STIFFNESS VS SIZE VS WEIGHT TRADE STUDIES
  - BEARING DESIGN & LUBRICATION STUDY

- THERMAL RADIATOR ROTARY JOINT (TRRJ) ACTIVITIES
  - ROTARY FLUID COUPLER PRELIMINARY DESIGN
  - PROOF-OF-CONCEPT ROTARY FLUID COUPLER
    MANUFACTURE & ASSEMBLE
    LMSC TESTING PHASE I & II



Solar Alpha Rotary Joint
— 130 inch diameter
— Discrete trundle bearings
— Redundant drive system
— Roll ring power/data transfer
— 360° continuous rotation



Radiator Rotary Joint
-- 21-inch diameter angular contact bearing
- Rotary fluid coupling
- Roll ring data/signal transfer
- +/- 100 deg rotation

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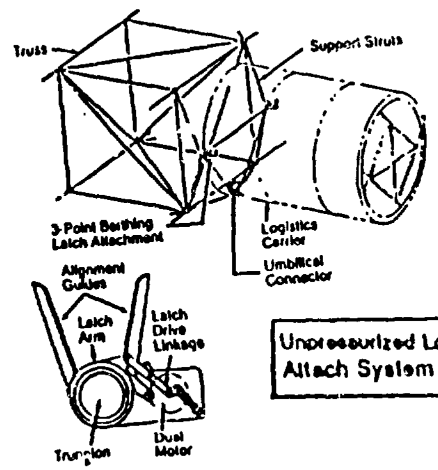
- <u>UNPRESSURIZED LOGISTICS CARRIER (ULC) ATTACH SYSTEM</u>
  - CONCEPTS FOR WP-1 & WP-2 DIFFERED DURING PROPOSAL
  - ULC REQUIREMENTS FOR TYPE OF SUPPLIES AND THE LOCATION ON THE STATION ARE UNDEFINED.



Unpressurized Logistic Module Attach System

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- <u>OTHER MECHANISMS</u>
  - <u>AIRLOCK HATCH</u>
    - CREW LOCK HATCH TRADE STUDY IS UNDERWAY TO SELECT A DESIGN CONCEPT
  - <u>ULC UMBILICAL MECHANISM</u>
    - BOTH WP-1 & WP-2 HAVE LEVEL III REQUIREMENTS
    - RESOLUTION OF THIS OVERLAP IS BEING WORKED THROUGH PROJECT OFFICE
  - <u>ASTRONAUT POSITIONING SYSTEM</u> (ON MT FOR USE ON AWP)
    - DESIGN REQUIREMENTS ARE BEING DEFINED/UPDATED
    - CONCEPTUAL LAYOUTS ARE COMPLETED
    - DESIGN TRADES ARE BEING PERFORMED (JSC ASSY PLANNING & EVA WORKING GROUPS & MDSSC ENGR BOARD REVIEWED) (JSC MECHANICAL GROUP TO STUDY TRADES)

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EVOLUTION ISSUES

- SSF IS EXPECTED TO GROW TO MEET EVER INCREASING REQUIREMENTS

- THE STRUCTURES SUBSYSTEM WILL HAVE TO ACCOMMODATE AND ENABLE STATION GROWTH REQUIREMENTS
  - PROVIDE ADDITIONAL STRUCTURE
  - INCREASE STRENGTH/STIFFNESS OF EXISTING STRUCTURE
  - REPAIR AND REPLACEMENT OF DAMAGED STRUCTURE

- METEROID AND DEBRIS PROTECTION IS AN ISSUE THAT PREVAILS DURING GROWTH PHASE

- THE STATION LEVEL OF ACTIVITY IS EXPECTED TO BE VERY EXTENSIVE, REQUIRING INNOVATIVE APPROACHES TO PROVIDING STRUCTURAL HARDWARE
  - SERVICING (FAYLOADS, OMV, PLATFORMS, etc.)
  - CONSTRUCTION ACTIVITIES (LARGE HEATSHIELDS, etc.)

STRUCTURES AND MECHANISMS

DISCUSSION SESSION

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STATION EVOLUTION WILL RESULT IN EXTENSIVE CHANGES FOR THE STRUCTURES AND MECHANICAL SUBSYSTEMS. SOME OF WHICH ARE:

- LARGER STRUCTURES, ADDITIONAL MECHANISMS
- DIVERSE AND INCREASINGLY MORE COMPLEX SUBSYSTEMS TO ACCOMMODATE ON THE STATION STRUCTURE
- FREQUENT MODIFICATION OF THE STRUCTURAL AND MECHANICAL HARDWARE TO ACCOMMODATE THE NEW REQUIREMENTS

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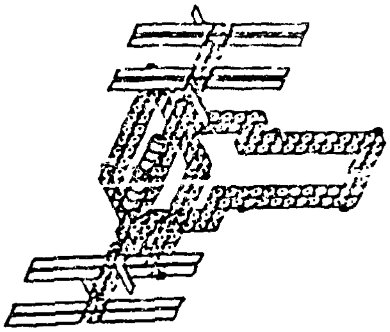

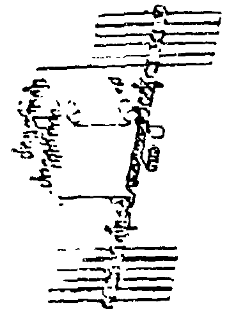

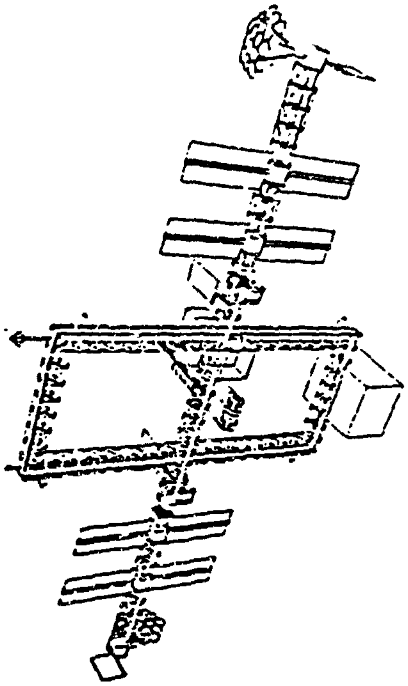

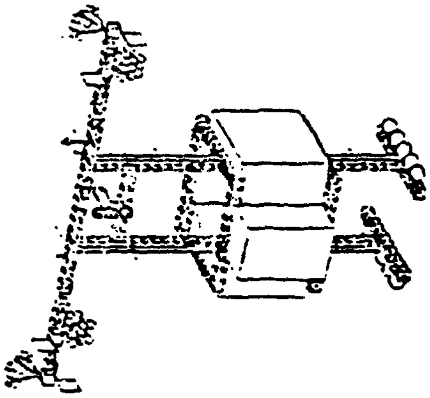

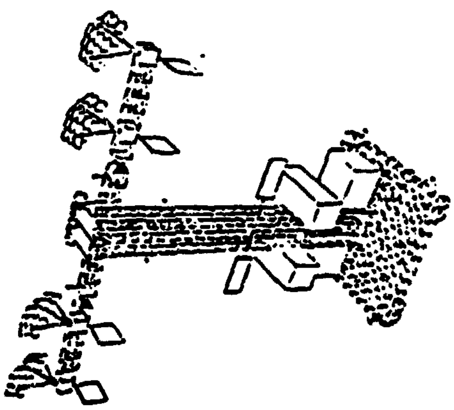

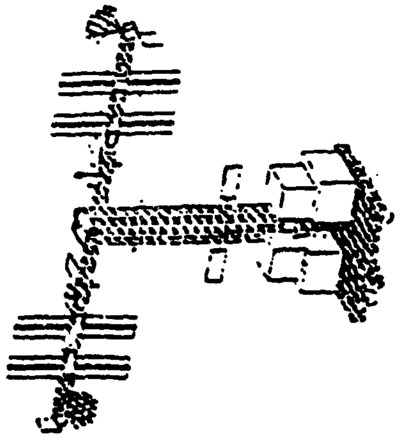

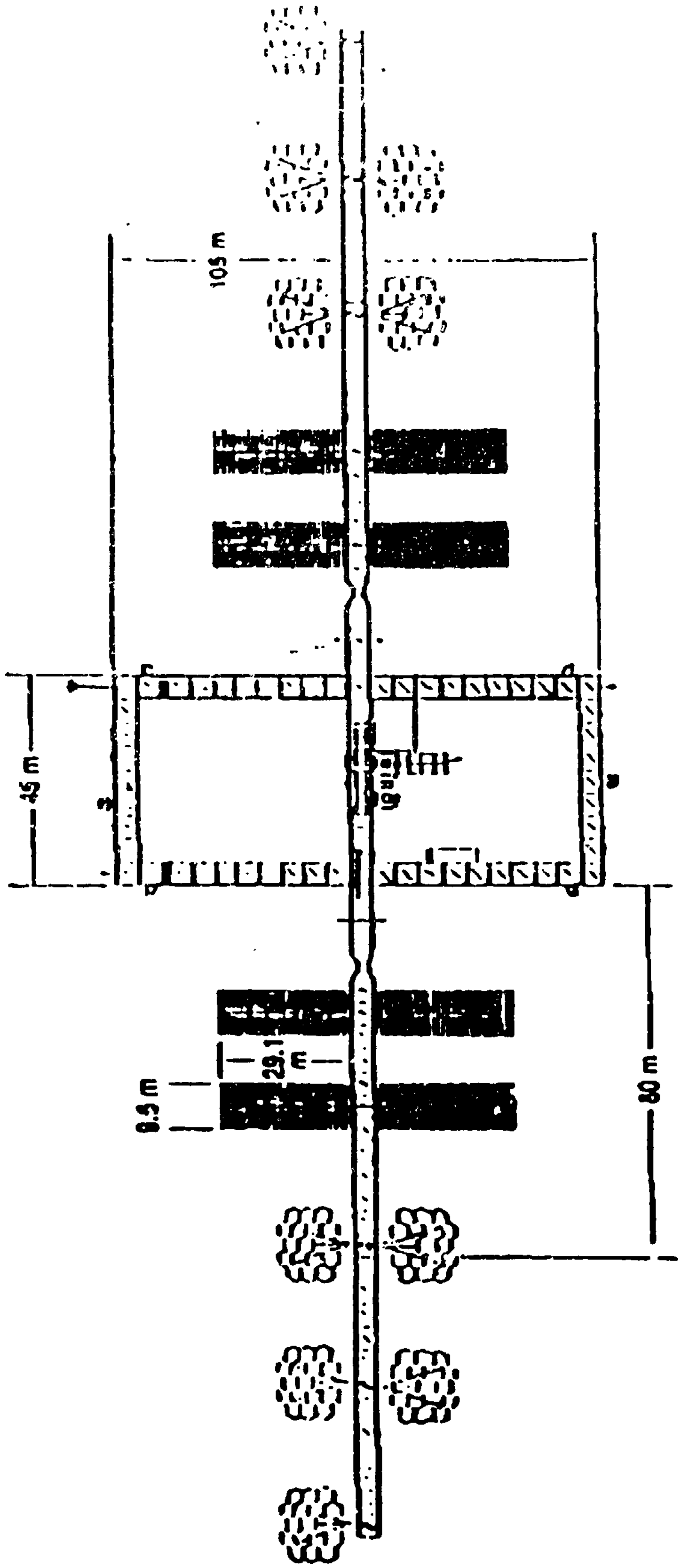

Figure 6.2.1. 325-kW Growth Power System

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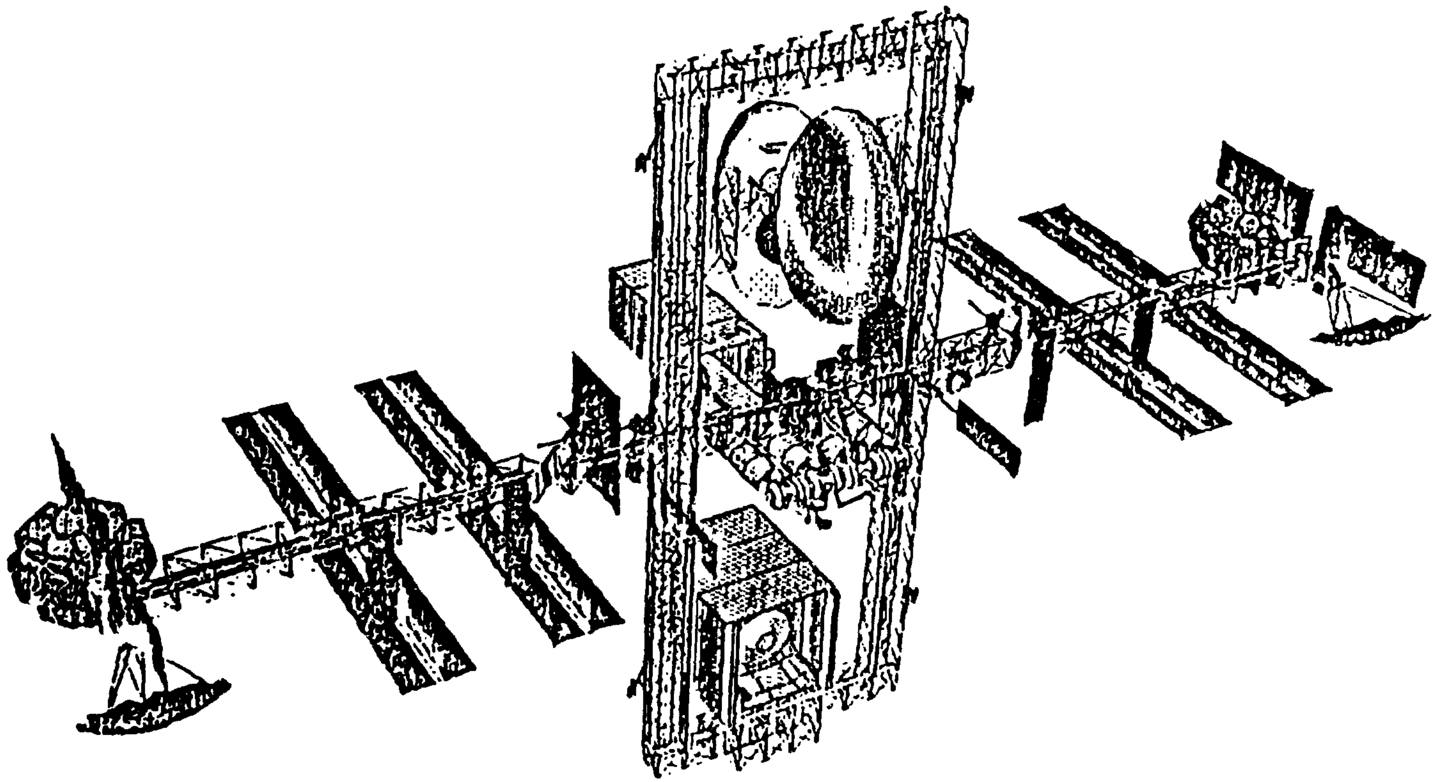
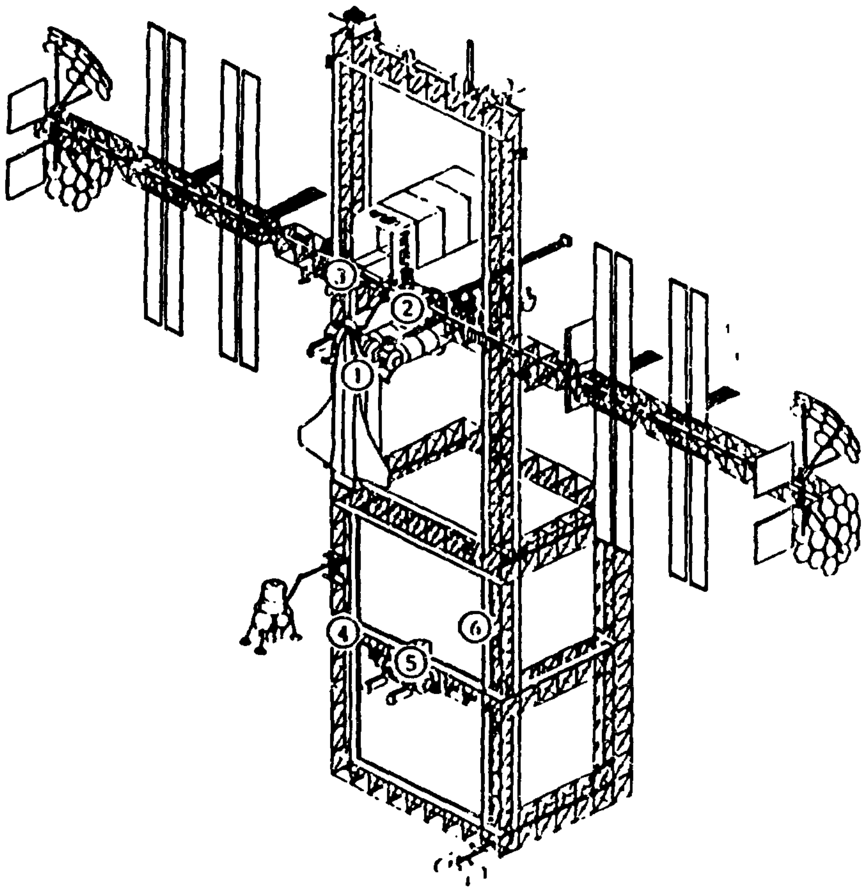


LaRC LUNAR/MARS TN

NASA/JSC
DR. KORNEL NAGY
713-483-8830



LaRC LUNAR TN

Mass: 612 mt
Hangar: 102,375 m^3

- ISSUES AND CONSTRAINTS FOR EVOLUTION OF STRUCTURAL AND MECHANICAL HARDWARE
  - THE DESIGN OF THE HARDWARE IS PRESENTLY FOR THE PMC CONFIGURATION
    - LOADS
    - SIZING
    - PERFORMANCE (DOCKING,BERTHING, etc.)
  - OPPORTUNITIES FOR REPAIR AND SERVICING OF STRUCTURAL AND MECHANICAL HARDWARE CAN BE SEVERELY LIMITED IN EVOLUTION PHASE BY
    - INCREASING NUMBER OF COMPONENTS
    - LIMITED CREW AVAILABILITY (EVA,IVA)
      - CREW WILL BE PERFORMING EXTENSIVE MISSION RELATED TASKS
    - LIMITED SPARES CAPABILITY

- ISSUES AND CONSTRAINTS FOR EVOLUTION OF STRUCTURAL AND MECHANICAL HARDWARE (CONT'D)

  - MINIMUM WEIGHT DESIGN IS A PERMANENT REQUIREMENT
  - METEROID AND DEBRIS PROTECTION IS A PERMANENT REQUIREMENT
    - MORE CHALLENGING WITH LARGER PAYLOADS
  - THE MASS AND VOLUME OF PAYLOADS WILL INCREASE
    - OTV 100 TO 200 KLBS RANGE
    - LTV 400 TO 500 KLBS RANGE
    - MTV 1000 TO 1500 KLBS RANGE
  - THE SERVICING OF LARGE VEHICLES MAY INCLUDE FUELING OPERATIONS
  - THE MOVEMENT AND MANIPULATION OF LARGE PAYLOADS WILL BE REQUIRED

Structures/Materials

Invited Presentations

22-13

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p. 23

STRUCTURAL TECHNOLOGY CHALLENGES FOR EVOLUTIONARY GROWTH OF SPACE STATION FREEDOM

HAROLD H. DOIRON
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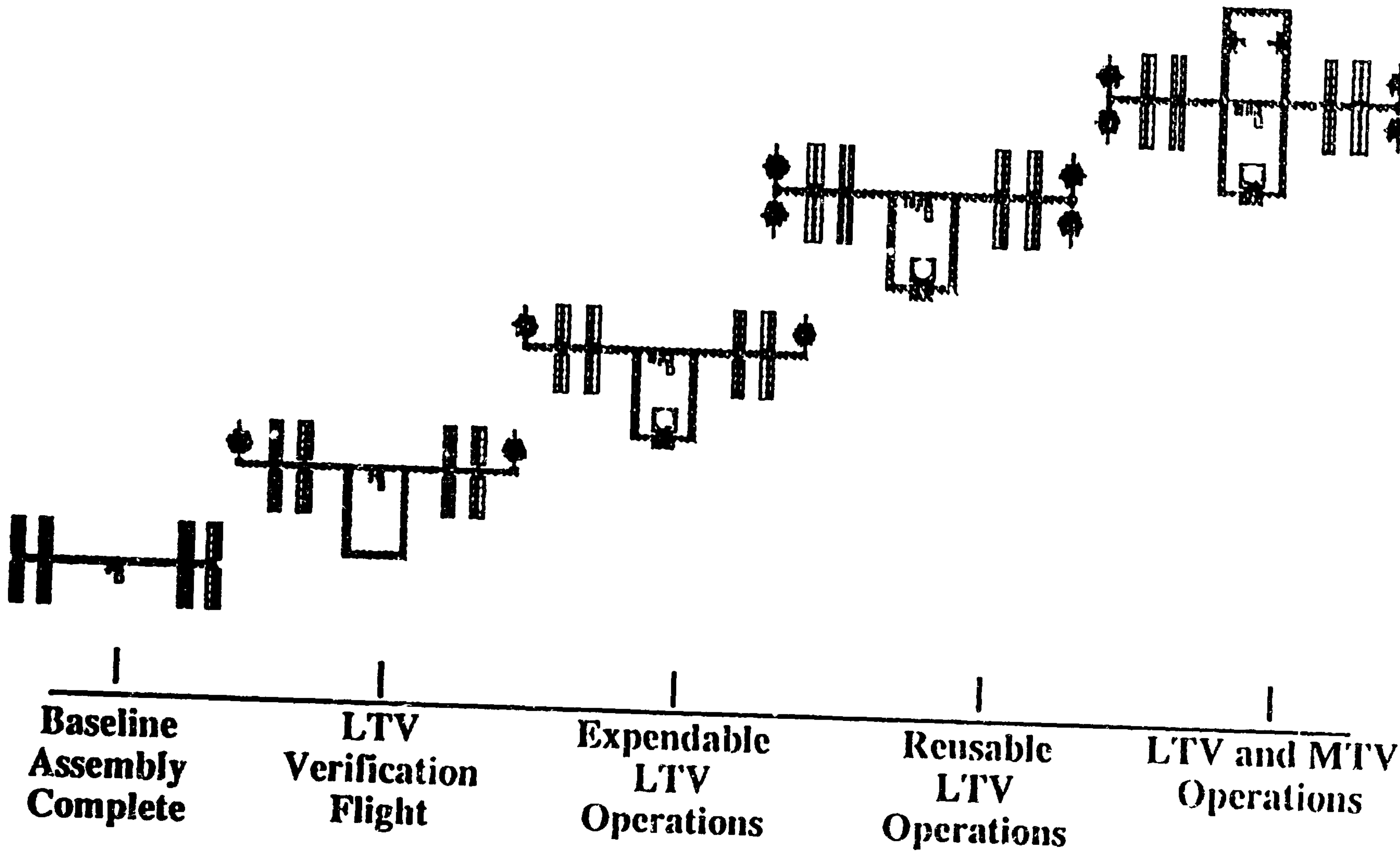
A proposed evolutionary growth scenario for Space Station Freedom was defined recently by a NASA task force created to study requirements for a Human Exploration Initiative. The study was an initial response to President Bush's July 20, 1989 proposal to begin a long range program of human exploration of space including a permanently manned lunar base and a manned mission to Mars. This growth scenario evolves Freedom into a critical transportation node to support lunar and Mars missions.

The growth scenario begins with the Assembly Complete configuration and adds structure, power and facilities to support a Lunar Transfer Vehicle (LTV) verification flight. Evolutionary growth continues to support expendable, then reusable LTV operations, and finally, LTV and Mars Transfer Vehicle (MTV) operations.

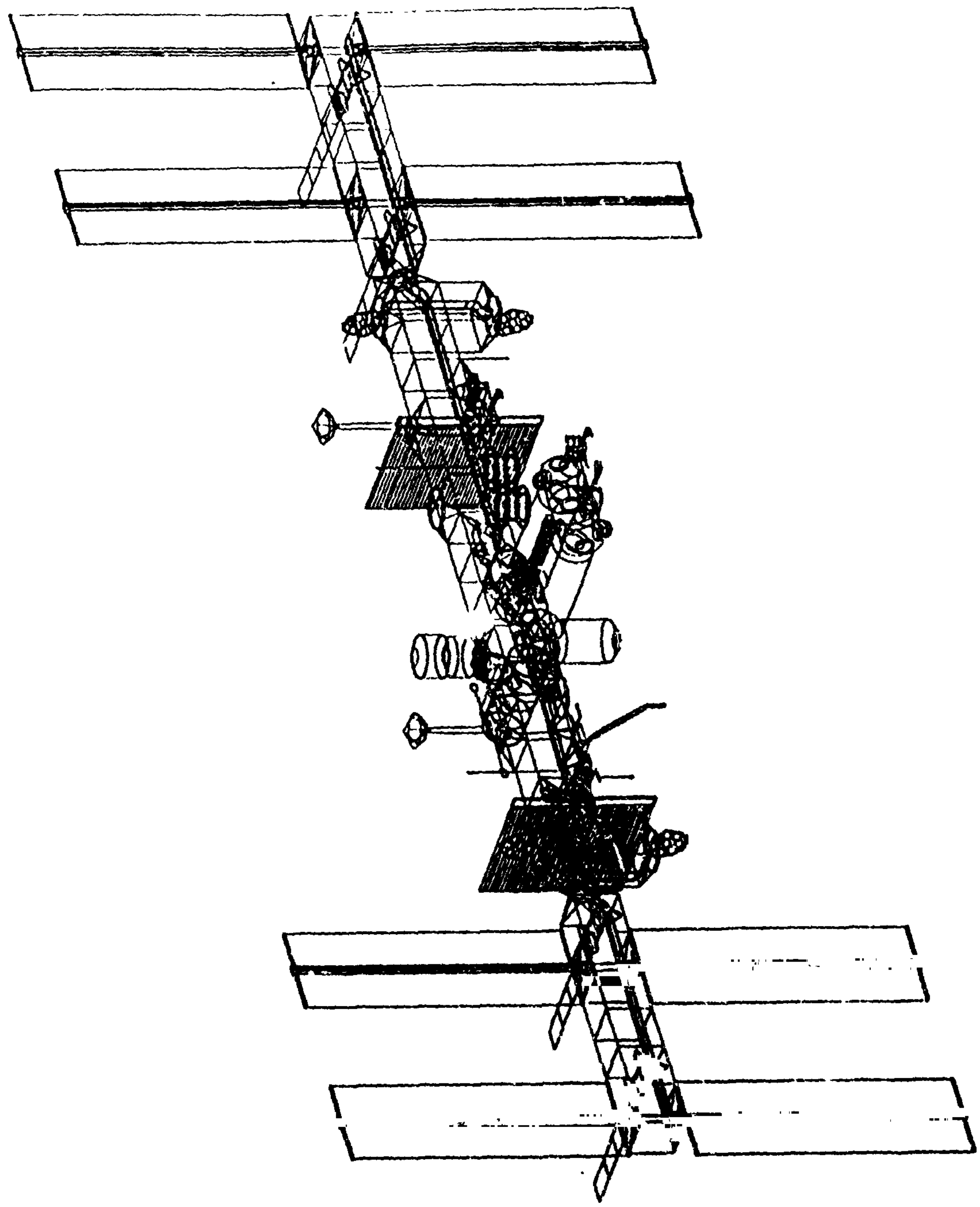
The significant structural growth and additional operations creating new loading conditions will present new technological and structural design challenges in addition to the considerable technology requirements of the baseline Space Station Freedom Program.

This briefing will review several structural design and technology issues of the baseline program and identify related technology development required by the growth scenario.

TRANSPORTATION NODE EVOLUTIONARY GROWTH



ASSEMBLY COMPLETE CONFIGURATION



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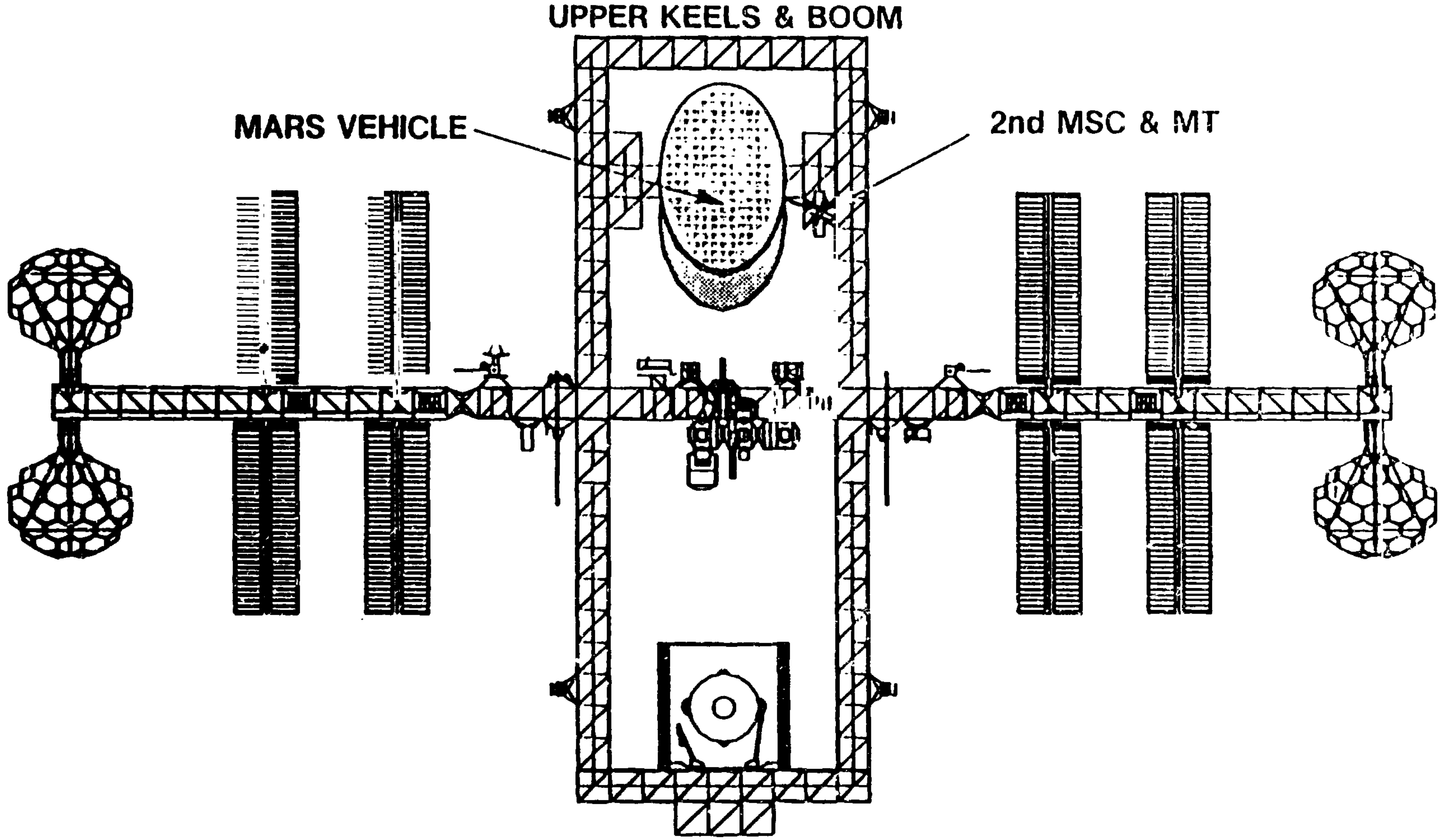
LTV & MTV OPERATIONS CONFIGURATION



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The Space Station Freedom and evolutionary growth configuration structures must be light weight with adequate strength to withstand imposed on-orbit loads, have adequate stiffness to preclude adverse structural/control interaction, allow for rapid and/or automated construction to minimize EVA time, be compatible with astronaut handling and translation requirements, and incorporate materials which will allow structural certification for a design life in excess of 30 years in the low earth orbit environment. In addition, the structure must be tolerant to damage from meteoroid and debris impacts or other accidental damage, allow for inspection and replacement of damaged structural members, and allow for growth to larger configurations.

These requirements present significant challenges for Space Station Freedom structural design. Growth requirements further drive the design to light-weight, stiff structures with dynamic characteristics which avoid adverse control systems interaction and which are capable of accommodating larger bending moments created by truss and keel extensions and new loading conditions.

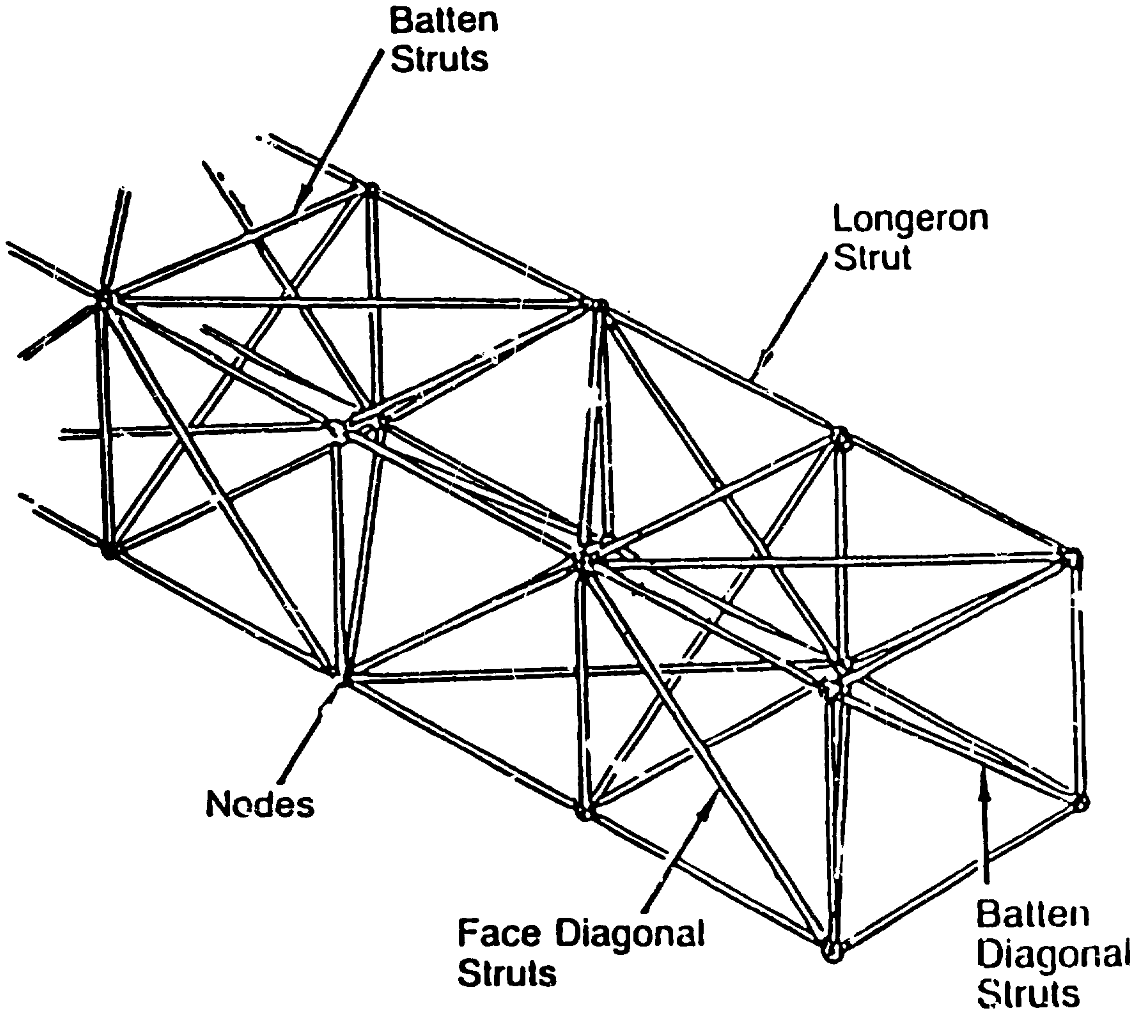
SPACE STATION FREEDOM STRUCTURAL DESIGN DRIVERS

- Light weight
- Adequate Strength
- Stiffness
- Rapid Construction
- Astronaut Handling/Translation
- 30+ Year Design Life
- Damage Tolerance
- Damage Inspection and Repair
- Growth Capability

The current five meter erectable truss design is a Warren truss utilizing alternating face diagonals and batten diagonals. Compared to an orthogonal tetrahedral truss, the alternating face diagonals offer 50 percent more torsional stiffness with one strut out (damage tolerant) and alternating batten diagonals provide greater lateral stability at the truss nodes with one strut out. Damage tolerance of the truss is achieved by requiring that the truss carry limit loads with a factor of safety of 1.0 with any one strut removed. The truss longeron and batten struts are 5.0 meters long (truss node center to truss node center) and the face and batten diagonals are 7.07 meters in length. Currently, the strut outer diameters are restricted to 2.0 inches to accommodate astronaut handling and hand-hold translation requirements.

The strut tubes are 30 msi modulus filament-wound graphite epoxy with wall thickness to be selected to accommodate design loads. A 0.005 inch thick aluminum foil is bonded to the outer surface of the graphite epoxy tubes for atomic oxygen and ultraviolet radiation protection. The graphite epoxy tubes are bonded and bolted to aluminum end fittings which contain the joint mechanism for attaching struts to truss nodes.

FIVE METER ERECTABLE TRUSS

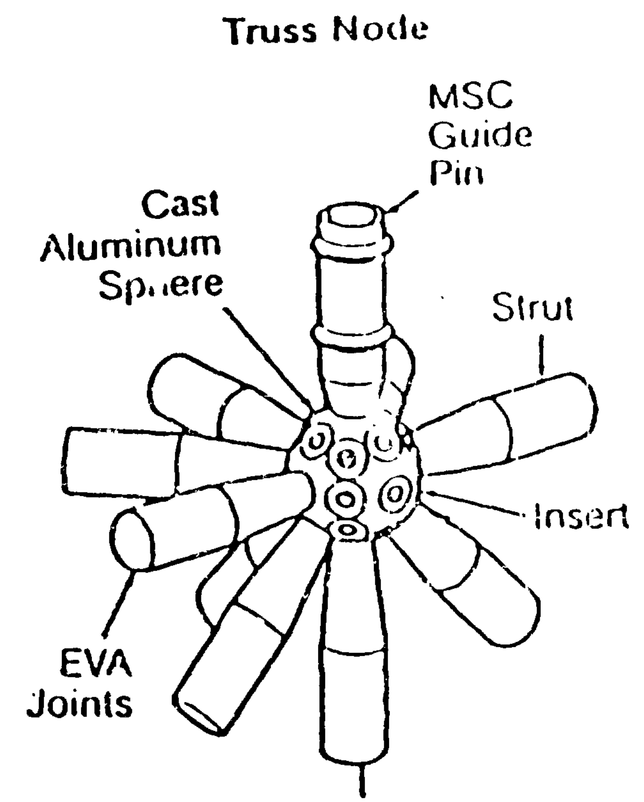


The truss nodes are 105 mm diameter hollow cast aluminum spheres with 26 machined flats containing inserts. The truss strut joint stubs and Mobile Transporter guide pins are bolted to the node at any of the 26 attach points. The attach points are designed to allow for unlimited orthogonal growth of the truss without interrupting the truss pattern. The joint stubs and MSC guide pins are bolted to the truss nodes prior to flight and pairs of truss nodes are pre-assembled to batten struts (in dumbbell fashion) to reduce EVA time on-orbit.

Joint mechanism selection has not been completed, but several mature designs have been tested and appear to be acceptable.

TRUSS NODE

- Hollow cast aluminum sphere 105mm (4.13 in.) in diameter
- 26 machined flats with inserts
- Truss joint stubs and MSC guide pins are bolted to the node at any of the 26 attach points
- Attach points optimized to allow unlimited orthogonal growth without interrupting the truss pattern



Preliminary loads analyses have been conducted for the Permanently Manned Configuration and Assembly Complete configurations of Space Station Freedom. Loading events from Orbiter docking and plume impingement, module berthing, reboost and EVA and IVA crew activity and exercise were considered. The major structural loading events were found to be associated with Orbiter docking dynamics and RCS jet plume impingement on solar arrays, module berthing dynamics associated with abnormally high contact velocity resulting from a runaway manipulator arm and crew loads imposed during an inadvertent push-off from the 5 meter truss near the outboard ends of the truss.

These loading events created significant bending response of solar array masts and bending and torsional responses of the 5 meter truss. Orbiter RCS jet plume impingement on the large area solar arrays has been found to create particularly large loads on solar array masts and the 5 meter truss. These loads can be significantly affected by Space Station and Orbiter operational restrictions which are currently being studied. Buckling of individual members of the solar array mast and 5 meter truss is the critical concern. In the case of the 5 meter truss, the long strut member length combined with a desire to limit the strut diameter to 2 inches for astronaut handling and translation hand-hold capability result in some truss members being designed by buckling loads.

DESIGN LOAD EVENTS

- Major Structural Loading Events
  - Orbiter Docking Dynamics
  - Orbiter RCS Jet Plume Impingement
  - Module Berthing
  - EVA Crew Loads

- Major Structural Load Concerns
  - Solar Array Masts Bending/Member Buckling
  - 5 Meter Truss Bending and Torsion Leading to Truss Member Buckling
    - 5 meter length longerons
    - 7.07 meter length diagonals
    - 2 inch OD struts for astronaut handling

Loads analyses should be conducted for various evolutionary growth configurations to identify loading events and characteristics and structural design sensitivity issues. New technology development requirements could also be identified such as automated docking systems designed to limit contact velocities and structural loads to allow for light weight structural design.

Extensions of the 5 meter truss in growth configurations create potential for larger bending moments on alpha gimbals and the central truss due to forces applied near truss tips such as RCS jet plume and crew EVA applied forces. Addition of keels creates highly loaded structure at the keel/transverse boom interfaces. Scarring the baseline structural design for growth requires more detailed knowledge of growth configurations and loading events from growth scenario operations.

Another structural design issue associated with evolutionary growth is that maximum loading conditions can occur during the construction operations before the final interim configuration is completed. Considerable effort on loads criteria development is needed for loading conditions which are associated with interim assembly configurations. Stochastic modeling of loading events may be required for efficient weight design. For example, if the critical load condition for an interim construction configuration results from docking dynamics, what degree of conservatism should be used for docking contact conditions for this one time event?

LOADS ISSUES FOR GROWTH CONFIGURATIONS

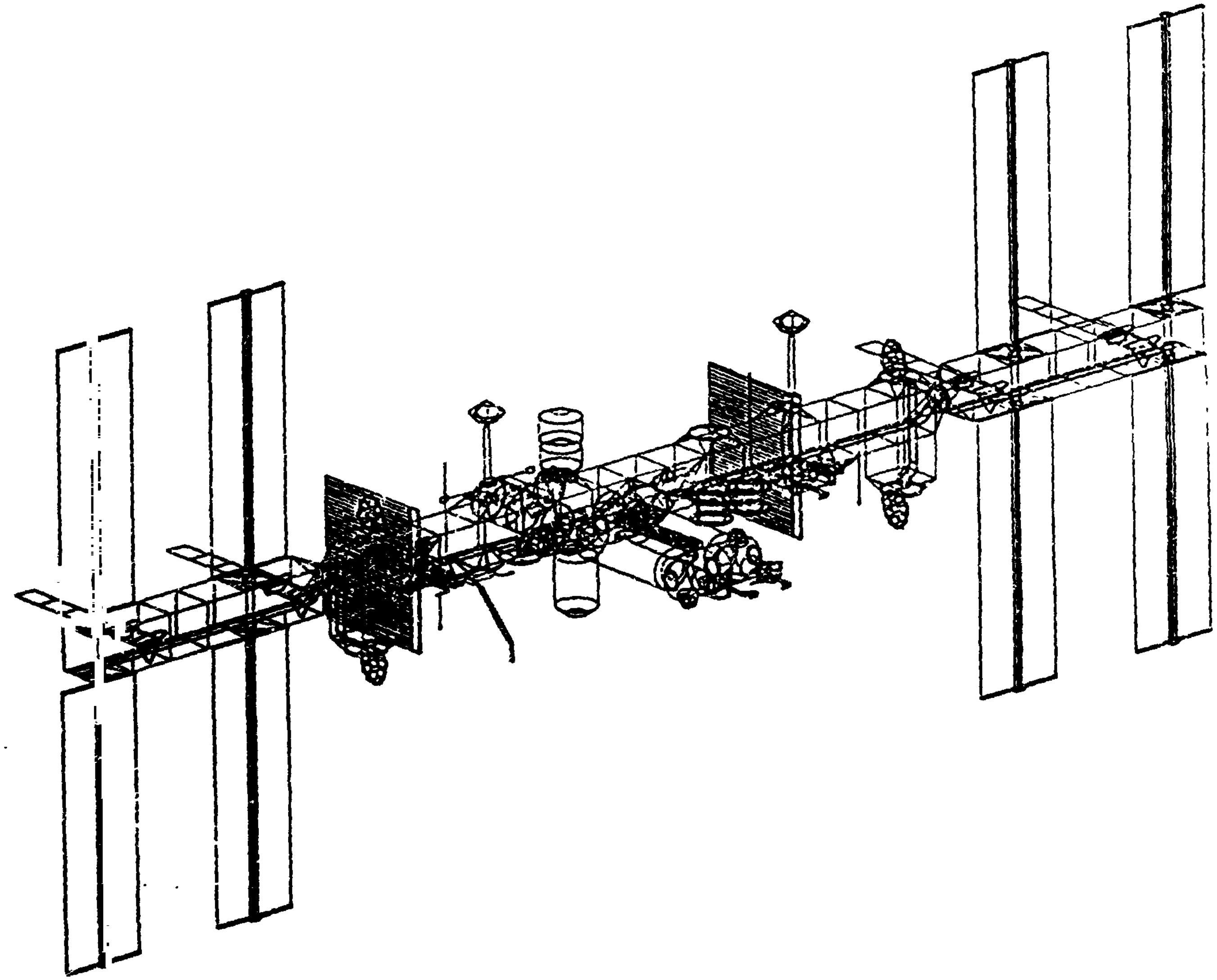
- Loads Analyses should be conducted to guide configuration selection and identify technology development requirements
- Extensions of the main 5 meter truss create potential for larger bending moments on alpha gimbals and central truss due to external forces applied near truss tips (plume, EVA)
- Addition of keels changes highly loaded areas of truss
- Spacecraft docking operations on upper and lower keels creates potential for large plume impingement and docking loads on transverse boom and keel structure
- Maximum loading events on individual truss members can occur during the construction process or for interim growth configurations. Loads criteria development including stochastic loads analyses required for weight efficient design.

One aspect of large space structures such as Space Station Freedom is the inability to perform modal tests of full scale integrated configurations on Earth due to structural strength, suspension and facility size limitations. Dynamically scaled models and/or on-orbit modal testing may become requirements for structural dynamics verification. The arguments for scale model and on-orbit modal testing of Space Station Freedom are strengthened by the requirement that the structure must grow to a much larger size where structural/control interaction is a greater concern and modal frequencies are lower.

NASA LaRC is developing scale model testing technology through its Dynamic Scale Model Technology (DSMT) program.

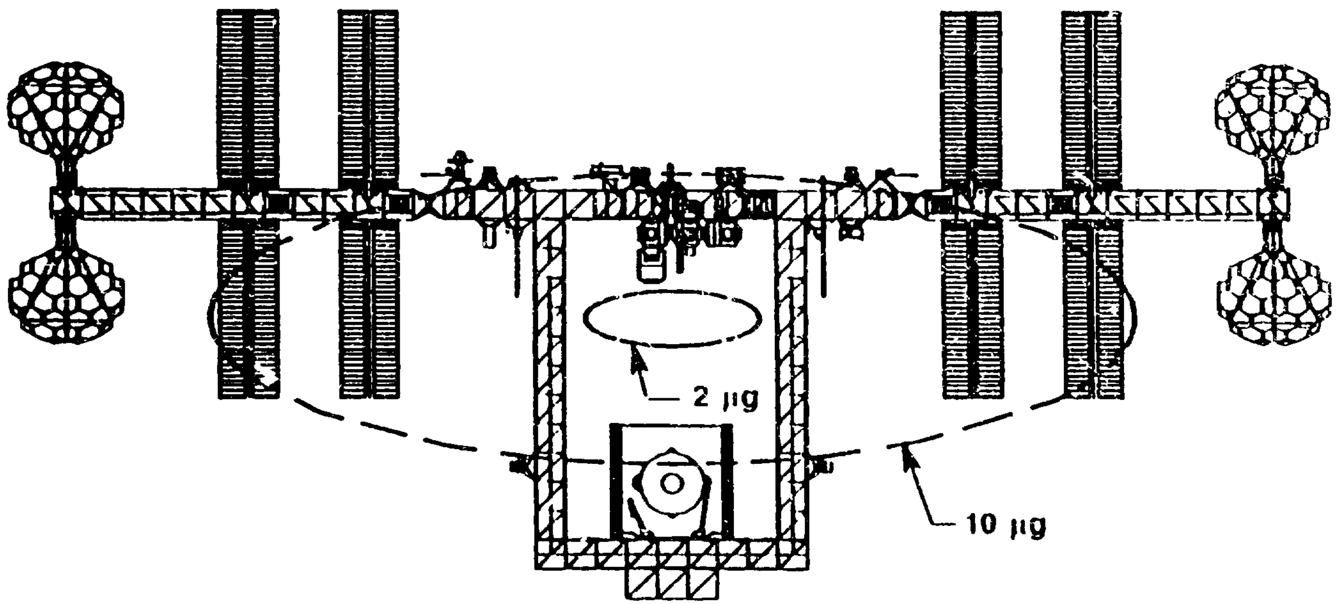
NASA OAST has proposed a Space Station Structural Characterization Experiment (SSSCE) as an augmentation and enhancement of Freedom on-orbit structural dynamics verification. In addition to validating structural dynamics prediction technology for large space structures in general, this experiment would provide critical data to verify acceptable dynamic characteristics of growth configurations of Space Station Freedom. A Phase A feasibility study has been completed and Phase B concept definition and experiment simulation studies indicate important structural modes can be identified from free decay responses of the structure to reboost and/or intentional excitation from RCS thrusters. The experiment is being designed to have minimal impact on Freedom design and operations, and makes use of the existing Data Management System for data acquisition using accelerometers mounted to truss nodes and modules. Development of optical dynamic measurement technology has been identified as an attractive alternative to accelerometer measurements, especially for larger structures and long service life of the measurement system.

STRUCTURAL DYNAMICS VERIFICATION ISSUES



Some concern has been expressed that evolutionary growth of Freedom towards a primary role as a transportation node may compromise its role as a microgravity research laboratory due to degradation of quasi-static microgravity levels in laboratory modules caused by increased drag and center of mass movement away from laboratory modules. When dynamic aspects of the microgravity problem are considered, this concern may not be a major issue. Transient accelerations due to crew motions and exercise can be one to two orders of magnitude greater than drag or gravity gradient quasi-static G-levels due to rigid and flexible body responses of the structure. In previous studies of crew exercise and activity disturbances, as much as 2/3 of the transient acceleration was due to rigid body accelerations. As the Space Station grows more massive, the rigid body accelerations produced by crew motions will decrease linearly with mass increase. The relative importance of transient accelerations to quasi-steady acceleration for microgravity research is not well understood. A Microgravity Disturbance Experiment is planned for the STS-32 mission to further explore the effects of microgravity transient disturbances on crystal growth. Additional research and technical interchange between the structural dynamics and microgravity research communities are needed to further define microgravity requirements and disturbance and experiment isolation requirements.

MICROGRAVITY ISSUES



Structural damage tolerance, detection, and repair of Freedom primary structure is required due to the long exposure to the meteroid and debris environment and impracticality of shielding all structural members. Truss struts can be replaced by disconnecting the mechanical joint between truss struts and truss nodes and installing a new strut. More difficult, however, is the task of identifying struts which must be replaced. A visual inspection approach is currently proposed, but will be very expensive in terms of astronaut EVA time and of questionable accuracy due to possibility of internal non-visible damage to the composite truss tubes. Damage detection technology development is a key program need which is exacerbated by larger growth configurations.

One promising technology is damage detection and location through modal identification techniques. Implementation of this concept would require a long service life structural dynamics measurement system. Such a system could be shared by the SSSCE and other users of structural dynamic data. Development of optical measurement systems for this purpose is a related technology need.

DAMAGE DETECTION AND REPAIR ISSUES

- Damage tolerance, detection and repair required
  - Meteoroid and debris environment
  - Shielding all primary structures not practical
- Truss has damage tolerance through single strut out capability
  - Struts are replaceable
- Major concern is detecting damaged struts
  - Visual inspection baselined
    - EVA intensive
    - Accuracy?
  - Technology development desirable
- Modal ID damage detection and location
  - Modal ID detection technology development required
  - Long service life dynamic measurement system required
    - Optical measurement technology development desirable

Evolutionary growth requirements for Space Station Freedom present significant structural and related technology challenges. Loads analyses of growth configurations are required to identify structural design and related technology issues and specify the critical scar requirements for the current Space Station Freedom Program. Technology development oriented to limiting imposed loadings from docking, berthing and proximity operations may be required to achieve weight efficient structural design. Criteria development for defining design load conditions for one time events during construction is needed. On-orbit modal identification methods development is needed to support damage detection and structural verification requirements. Long life certification of materials in the low Earth orbit environment is a concern and requires further technology development.

Finally, the technology issues associated with structures and evolutionary growth are not just structural issues. They are multidisciplinary in nature and will require considerable interaction between structural engineers and experts in other disciplines to achieve the best solutions to problems presented by evolutionary growth.

CONCLUDING REMARKS

- Evolutionary growth capability presents significant structural and related technology challenges
- Loads analysis of growth configurations required to identify structural design and related technology development issues and specific scar requirements for Freedom
- Loads criteria development for construction phase required
- On-orbit modal identification methods development
  - Structural dynamics verification
  - Damage detection
- Long life certification of materials
- Technology issues are multidisciplinary, not just structural issues
  - Controls/structural interaction
  - Microgravity
  - Load limiting related technology (docking, berthing, prox ops, etc.)
  - Damage detection, inspection, repair
  - Meteoroid and debris protection
  - Astronaut compatibility

Long Duration Exposure Facility (LDEF) Benefits/Impact on Future Space Systems

Darrel Tenney

NASA Langley Research Center

Technology for Space Station Evolution Workshop
January 16-19, 1990
Dallas, Texas

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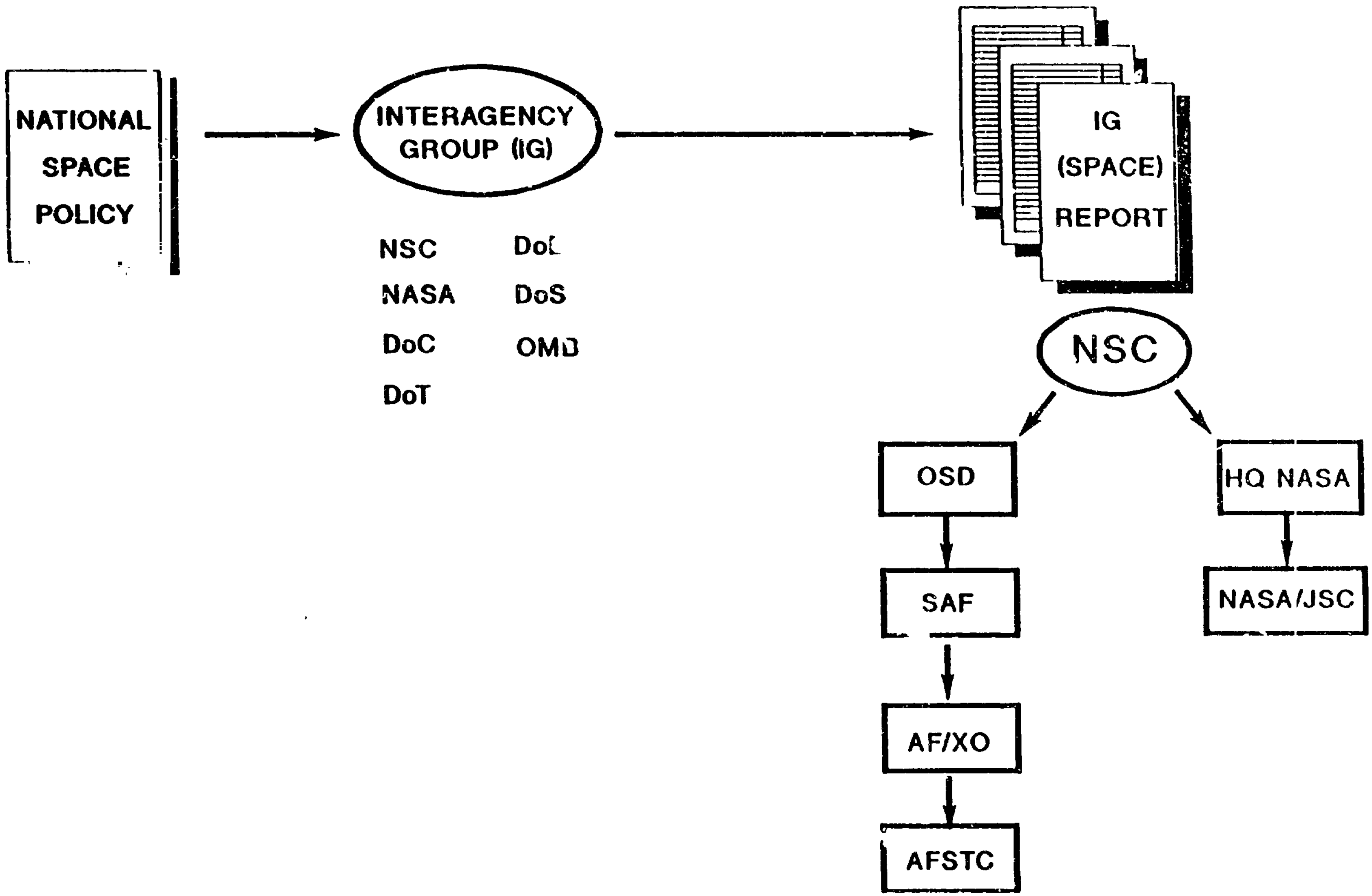
PAPER UNAVAILABLE AT TIME OF PUBLICATION

APPROACHES TO DEALING WITH METEOROID AND ORBITAL DEBRIS PROTECTION ON THE SPACE STATION

DONALD J. KESSLER
NASA-JSC/SN3
JANUARY 16, 1990

The National Space Policy of February, 1988, included the following: "All sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness." The policy also tasked the National Security Council, which established an Interagency Group, which in turn produced an Interagency Report. This report tasked both NASA and DoD to establish a joint plan to determine techniques to measure the environment, and techniques to reduce the environment.

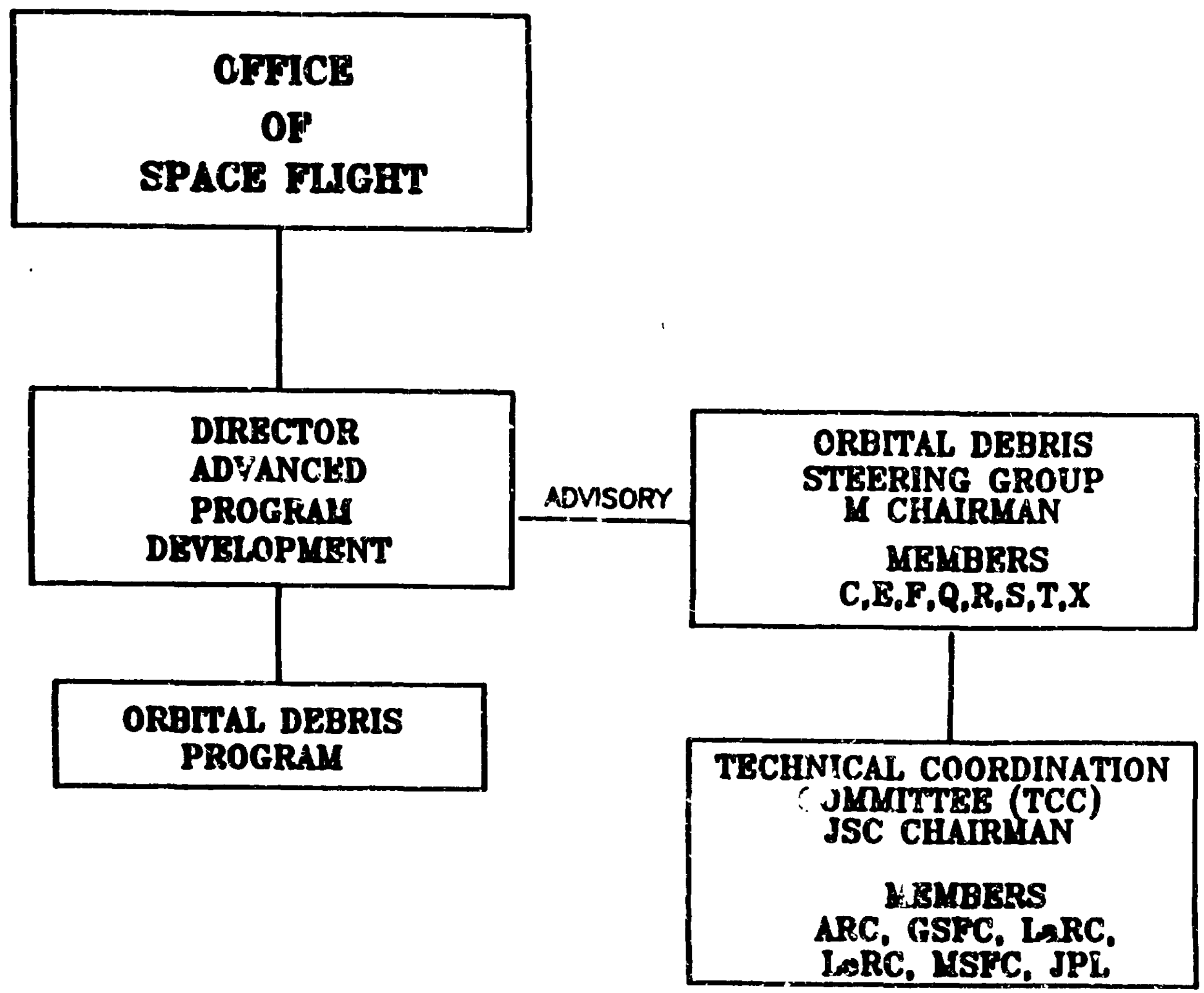
BACKGROUND


NATIONAL SPACE POLICY
INTERAGENCY GROUP (IG)
NSC
NASA
DoC
DoT
DoL
DoS
OMB
IG (SPACE) REPORT
NSC
OSD
SAF
AF/XO
AFSTC
HQ NASA
NASA/JSC

The NASA Administrator directed the Office of Space Flight to Chair an Orbital Debris Steering Group, with representatives from other NASA Offices. A technical Coordination Committee, chaired by the Space Science Branch at the Johnson Space Center was also established.

ORBITAL DEBRIS PROGRAM

MANAGEMENT STRUCTURE



The Johnson Space Center has been studying orbital debris for over 10 years, and has a comprehensive program which includes measurements of both small and large debris, model development, and hypervelocity impact testing. The current largest program is to development a orbital debris radar, with US Space Command, which will statistical monitor the 1 cm, and larger, environment. The largest justification of these measurements is to support Space Station.

NASA/JSC Orbital Debris Program

- Measurements
  - Radar: Maintaining USSPACECOM catalog, breakup measurements, radar development, re-entry radar
  - Optical/IR: GEODSS data acquisition, optical/IR studies, NASA portable telescope
  - Microparticle: PALAPA/WESTAR, LDEF, SOLAR MAX, witness plates, stratospheric dust collection, Space Station Cosmic Dust Facility
- Under development
  - Orbital Debris Radar (Joint USSPACECOM agreement)
  - Radar data processing facility
  - Debris Collision Warning Sensor (visible/IR Shuttle Experiment)
- Data management
  - Modeling: Breakup modeling, population evolution, microparticle environment, current environment assessment, environment forecasts
  - Data Interpretation: Uncorrelated target analysis
- Spacecraft shielding
  - Materials and shielding research, Space Station support, hypervelocity gun development, hypervelocity and low-velocity testing, vulnerability assessment
- Debris management
  - Debris removal, debris prevention
- Facilities
  - Image processing facility, hypervelocity impact research laboratory, electron microscopy laboratory, facility for optical inspection, material archives, telescopic laboratory

Space Station must deal with the entire spectrum of orbital debris sizes. Below 1 cm to 2 cm, shielding is planned; however, the weight of required shielding is sufficiently high that extra shuttle flights could be required to construct the Space Station. For this reason, the approach of adding shielding after the Space Station is constructed is likely. If so, the technique that shielding is added becomes important; since extra EVA also means extra risk, some new techniques of adding shielding may be required.

For sizes between 1 cm and 10 cm, there is currently no proven technique to defend against these particles. During the 30 year life of the Space Station, it is likely that such a size debris particle will collide with the Space Station, if no actions are taken. The collision would most likely be in a non-critical area; however, it would be sufficiently energetic that secondary ejecta would likely damage critical areas. Objects as large a 1 meter are in orbit, and not catalogued.

Collision avoidance is planned for all catalogued objects. A critical question, not yet resolved, is whether US Space Command orbital projections are sufficiently accurate to keep the frequency of maneuvers of the Space Station within acceptable limits.

ORBITAL DEBRIS ENVIRONMENT: ISSUES FOR SPACE STATION FREEDOM

DEBRIS SIZE RANGE	ISSUE	POTENTIAL SOLUTIONS	PROBLEMS TO SOLUTION IMPLIMENTATION
Less than 1 cm (2 cm)	Loss of critical elements due to direct impact; damage to non-critical elements due to direct impact and secondary ejecta.	• Shielding • Maintaince • Re-dundant systems	• Weight limitations - new materials - Add -on shielding • Additional EVA
1 cm to 10 cm (1 meter)	Loss of critical elements damage to non-critical elements due to secondary ejecta from direct impact of non critical areas. Potential loss of station from catastrophic collision.	• Increased Ground tracking capabilities • On-board collision warning sensor - Active shielding - Heavly shielded shelter - Directed energy diversion • Materials which minimize secondary ejecta	• Technology development
Larger than 10 cm (1 meter)	Loss of Station from catas[illegible] collision	• Collision avoidance using ground tracking	• US Space Command Limitations - Accuracy of tracking - Completeness of data • Frequency of maneuvers

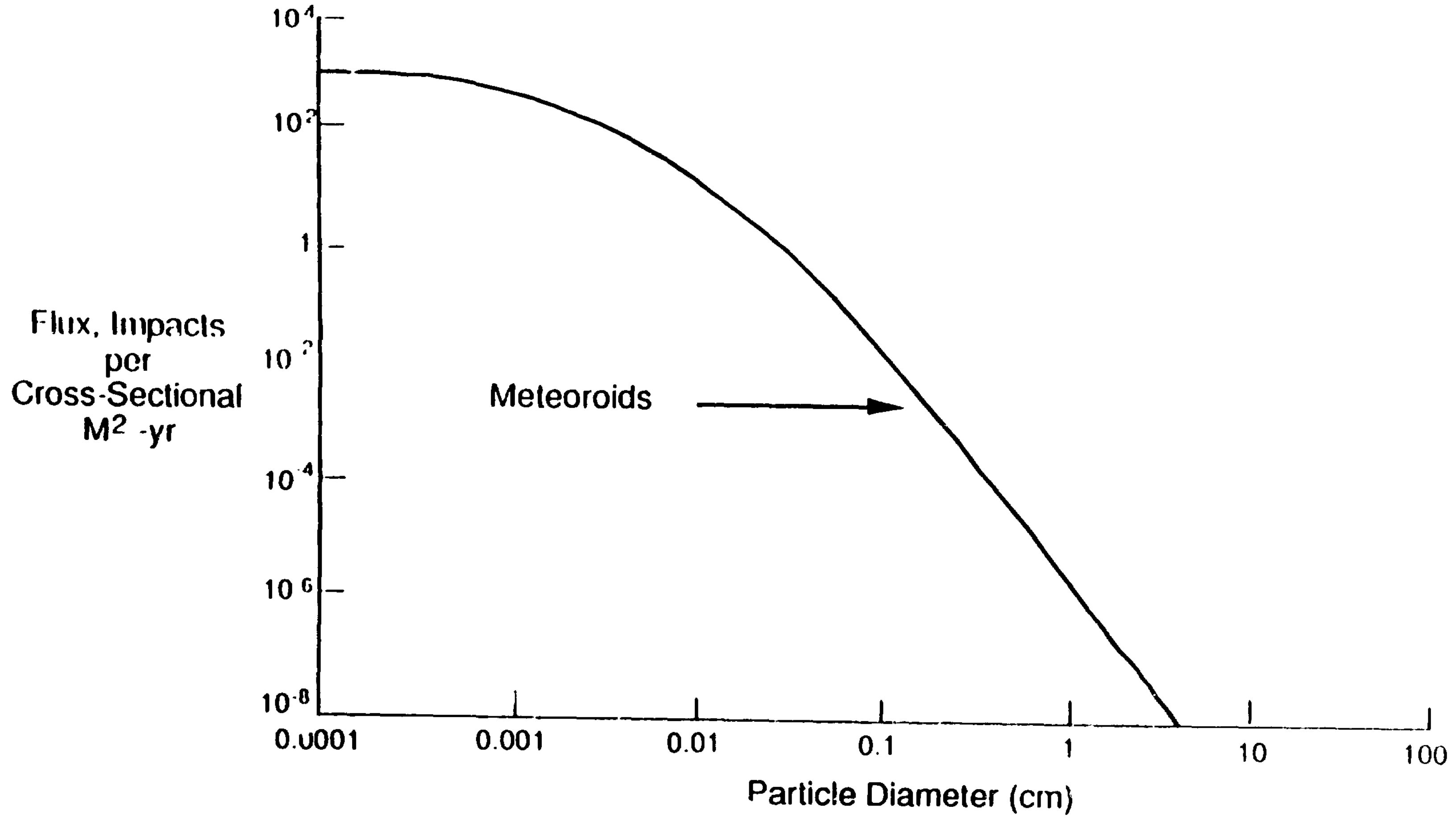
Knowledge of the meteoroid environment is primarily the result of the past 25 years of research. The understanding of the environment has not changed significantly since 1970. A very small amount of meteoroid mass is passing through Earth orbital space at about 20 km/sec; even so, meteoroids are a design consideration for the Space Station.

Meteoroid Background - Current NASA Understanding

- Best data from meteors, deep space sensors, lunar rocks, returned spacecraft surfaces, and early sensors requiring penetration
- Meteoroid orbits pass through Earth orbital space (none believed to be in Earth orbit)
- Less than 200 kg at altitudes below 2000 km at any one time (most approximately 0.1 mm in diameter)
- In the past, meteoroids have occasionally affected spacecraft design
  - Apollo, Skylab
  - Size range 0.3 mm to 3 mm most important
- In the future, meteoroids are expected to be more important
  - Larger spacecraft
  - Longer exposure
  - Lighter weight construction
  - Size range 0.1 mm to 1 cm will be important

The meteoroid environment used of to design spacecraft is given in NASA SP 8013, published in 1969, and shown here as a cross-section area flux. Assume the surface area of a critical element to be shielded is 100 sq. meters; its average cross-sectional area would be one forth of that, or 25 sq. meters. The average number of impacts on the area in 10 years would be given by N=FX25X10, where F is the cross-sectional flux given in the figure. If the desired probability of no penetration is 0.9955 during the 10 years, then N is approximately equal to 1-.9955, or N=0.0045. The design flux is then F=1.8E-5. From the figure, the design meteoroid size is then about 0.5 cm. That is, the protective shield must be designed to protect against a meteoroid 0.5 cm in diameter, traveling about 20 km/sec, in order to achieve this desired level of reliability.

Meteoroid Flux



Much larger than the meteoroid environment is the amount of mass "permanently" orbiting the Earth in the form of man-made objects. Most of the man-made mass is in relative large, old rocket bodies and payloads, vs. the relative small dust size for meteoroids. However, if only a small fraction of the man-made material were to fragment into the size distribution of meteoroids, the resulting flux would exceed the meteoroid flux. There many ways that the man-made objects can, and have, fragmented.

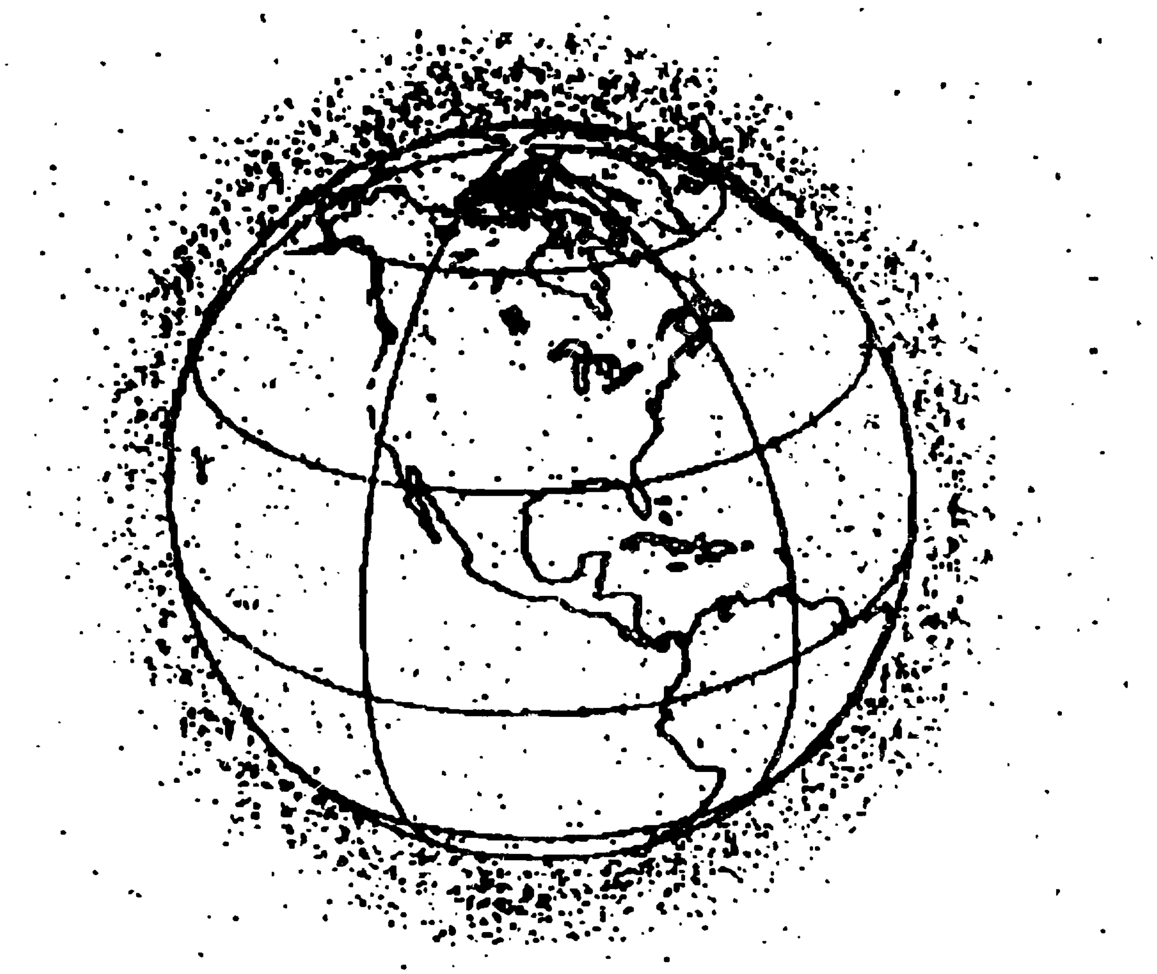
Orbital Debris Population

- Over 20,000 objects catalogued by U.S. Space Command, most "permanently" in Earth orbital space, about 7000 in orbit to date
- Approximately 3,000,000 kgm at altitudes below 2000 km (most approximately 3 meters in diameter)
- High intersection angles produce high collision velocities
- If only a small fraction (0.01%) of the mass were in a smaller size range the resulting environment would exceed the meteoroid environment in that size range. Possible sources of smaller objects are:
  - Explosions
  - Hypervelocity collisions
  - Degradation of spacecraft surfaces
  - Solid rocket motors firing in space

NASA

The orbital inclinations and altitudes of man-made objects are such as to cause the Earth to be surrounded almost uniformly by a shell. A spacecraft within that shell is almost equally likely to run into another orbiting object, independent of the direction of motion. Also the differences in the direction of motion between any two objects give relatively high encounter velocities, averaging about 10 km/sec.

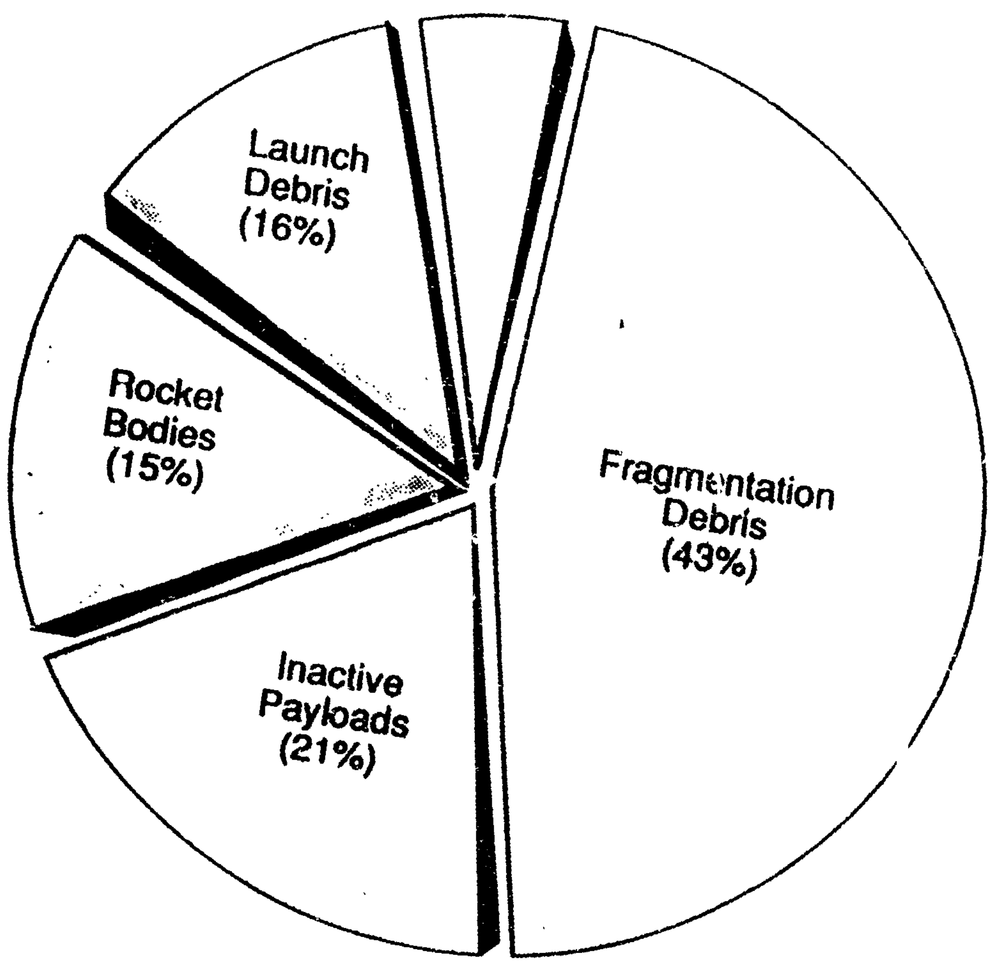
Snapshot of Cataloged Objects as Observed from a Point in Space



Only 5% of the catalogued population is operational spacecraft; most are the result of the approximately 100 explosions in orbit.

Cataloged Earth Satellite Population

19 August 1989



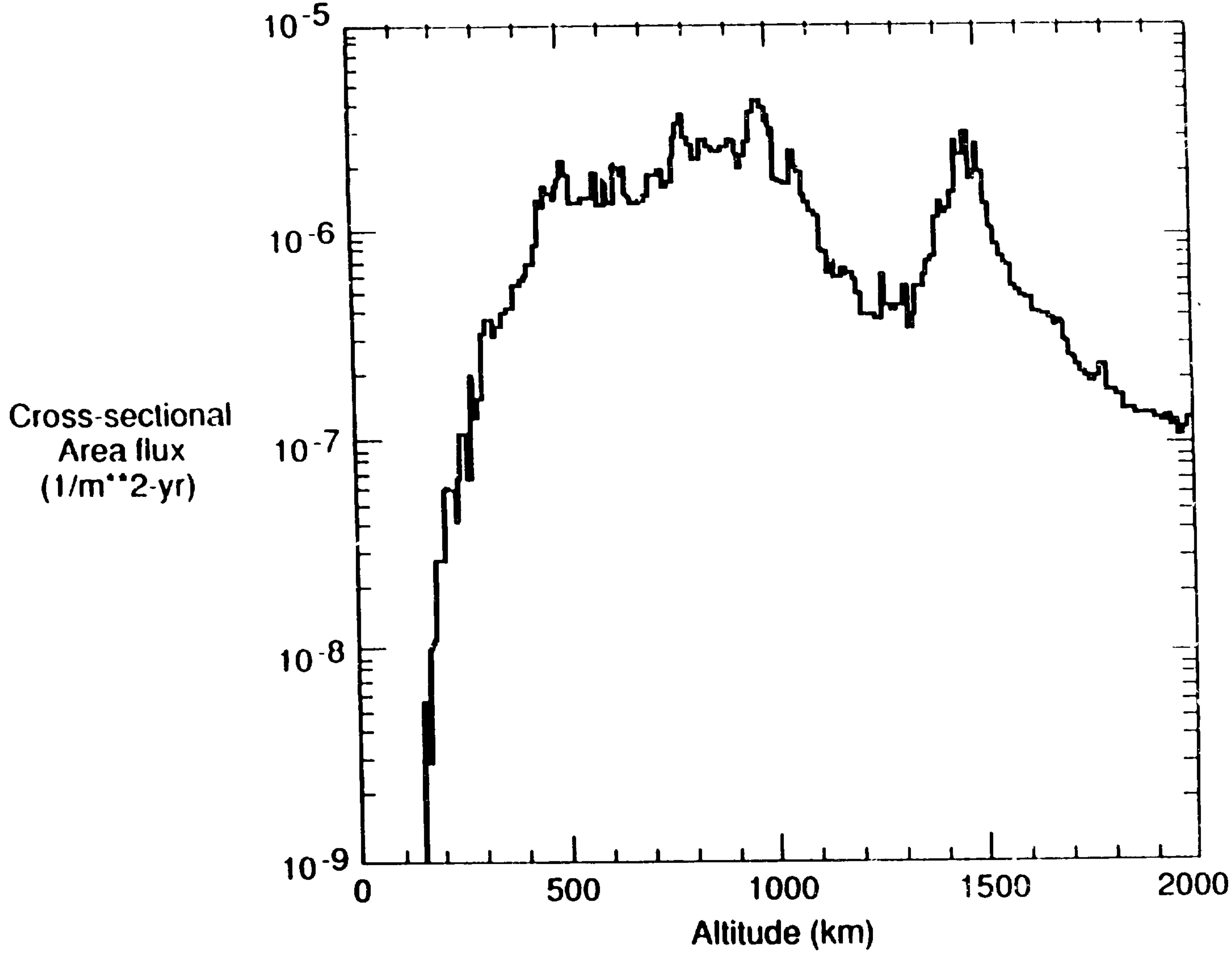
NASA

The flux from the 1987 catalogue is given here. The peaks in the fluxes at various altitudes are mostly the results of various breakups at those altitudes. If the Space Station were at about 450 km at this time, it would experience a flux of about 1E-6 per meter sq. per year. This means that there is about one chance in 100 every year of an object passing within 50 meters of the center of the space station, or about one chance in three over a period of 30 years if there were no change in the population.

US Space Command is also tracking a group of objects which are not catalogued, know as the analysis set. At altitudes below 500 km, the flux from the analysis set sometimes exceeds the flux from the catalogue; therefore, over 30 years, it is very likely that a collision with a catalogued or tracked object would occur, if there were no collision avoidance maneuvers. The current mission rule for the Shuttle is that it will consider maneuvering if a object is predicted to pass within a 2 km by 5 km by 2 km distance from the Shuttle. This is a cross-sectional area of about 40E6 sq. meters for the direction of most debris, and means that the Space Station would have to make 40 maneuvers per year if it used this mission rule. To reduce this rate means increasing the accuracy of the predicted miss distance so that unnecessary maneuvers are not performed.

USSPACECOM Cataloged Objects

January 1987



During 1987, there were a large number of breakups, many at low altitudes. By looking at radar tapes at various sites, we know that as many as 1000 trackable fragments were produced from some of these breakup; however, only a small fraction were ever catalogued before they reentered.

1987 Satellite Breakups

Catalogued Fragments as of January 10, 1988

Breakup Date	Satellite Name	Breakup Altitude (km)	Orbital Perigee (km)	Orbital Apogee (km)	Orbital Inclin. (deg.)	Trackable Fragments Estimated	Trackable Fragments Catalogued
1-28-87	COS1813	390	359	417	73	1000	190
7-26-87	COS1866	243	167	361	67	1000	9
9-18-87	ARIANE	?	246	36523	7	>15	1
9-21-87	COS1769	333	310	444	65	150	4
11-20-87	COS1646	406	401	434	65	150	25
12-17-87	COS1823	1485	1477	1523	74	>60	43
9-28-87 10-4-87	TIROS N	?	838	856	[illegible]9	0	3

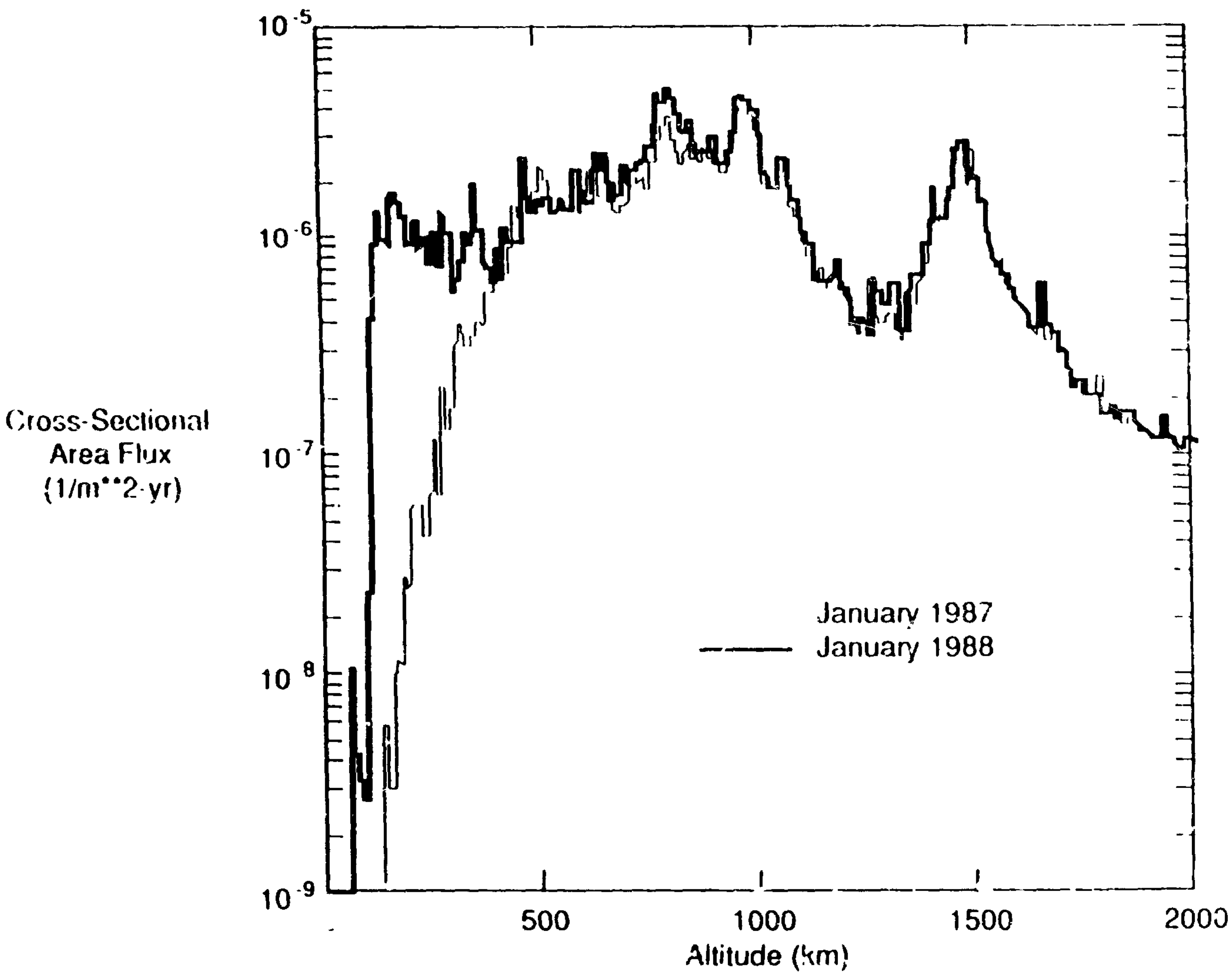
The estimated number of fragments was determined from radar data from individual radar sites.

NASA

The flux increases at low altitudes resulting from the cataloged fragments of the 1987 breakups alone were significant. If the Space Station were in orbit during this time the collision avoidance maneuver rate would have been significantly higher. However, the flux only remained this high for a few months before most of the fragments reentered.

USSPACECOM Cataloged Objects

January 1988



As solar activity increases, atmospheric density also increases, causing more debris to reenter, reducing the flux at lower altitudes. The 1990 solar activity may prove to be the highest in record keeping.

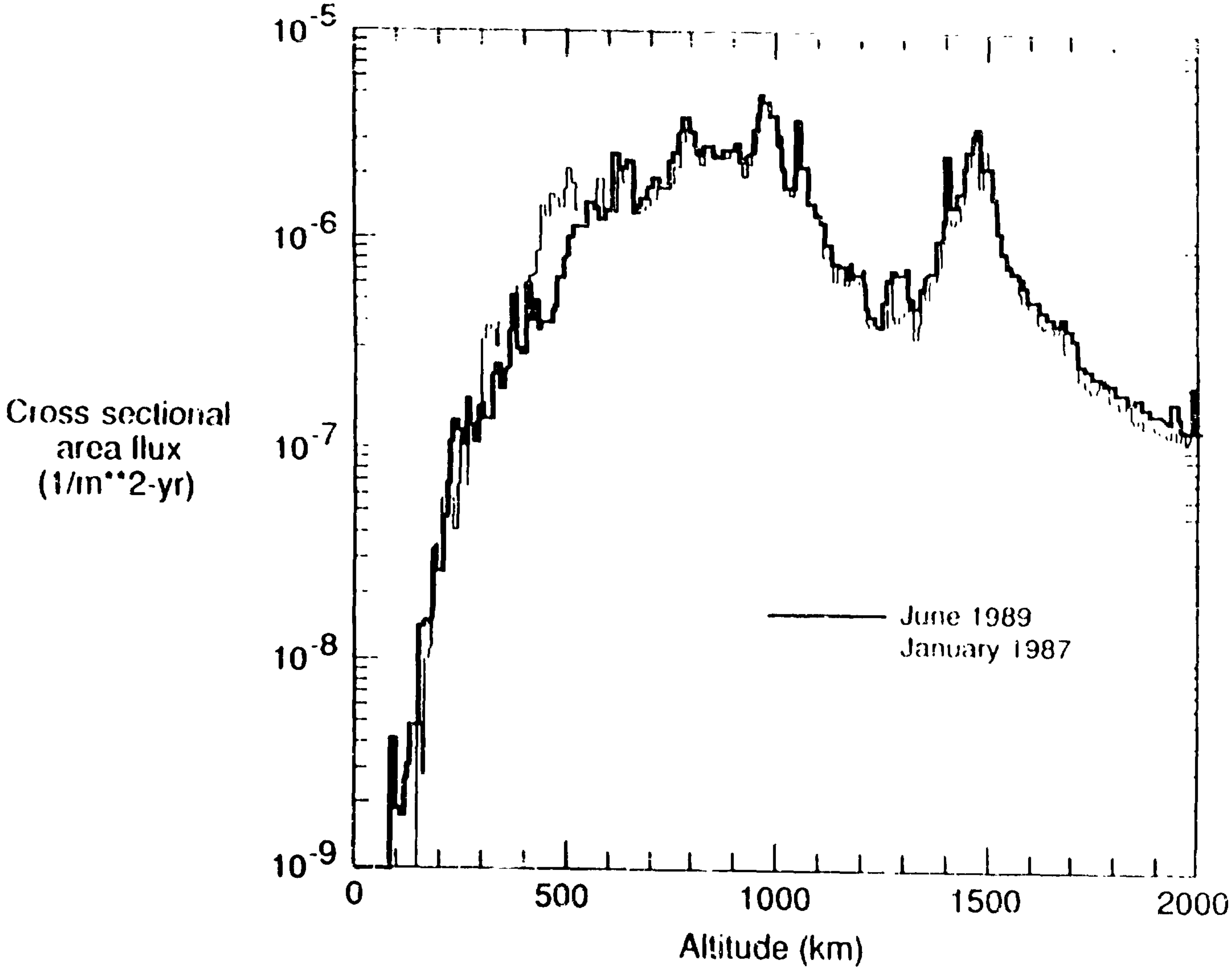
Relationship Between Solar Cycle, Atmospheric Density, Debris Population

- 11 year cycle
  - Measured by sunspot number and 10.7cm radio wavelength ($F_{10.7}$) Flux
  - Average cycle $F_{10.7}$ ranges between 70 and 150
  - Last cycle (peaked in 1981) was above 200
  - Current cycle expected to be about 250
- High solar activity heats upper atmosphere
  - Atmosphere expands, moves up
  - Upper atmosphere density increases
  - Satellites, debris decay more rapidly
- Debris population changes with solar activity depending on altitude
  - Above 500 km atmospheric density so low, population not changed
  - Below 500 km, very noticeable changes

The effect that the currently high solar activity has been to reduce the flux at altitudes below 600 km; however, the high solar activity is also likely to require that the altitude of the Space Station be increased; consequently the flux that the Space Station is exposed will likely remain the same. As the solar activity again decreases, the flux at low altitudes will increase back to about its 1987 values with debris previously at higher altitudes now at these lower altitudes.

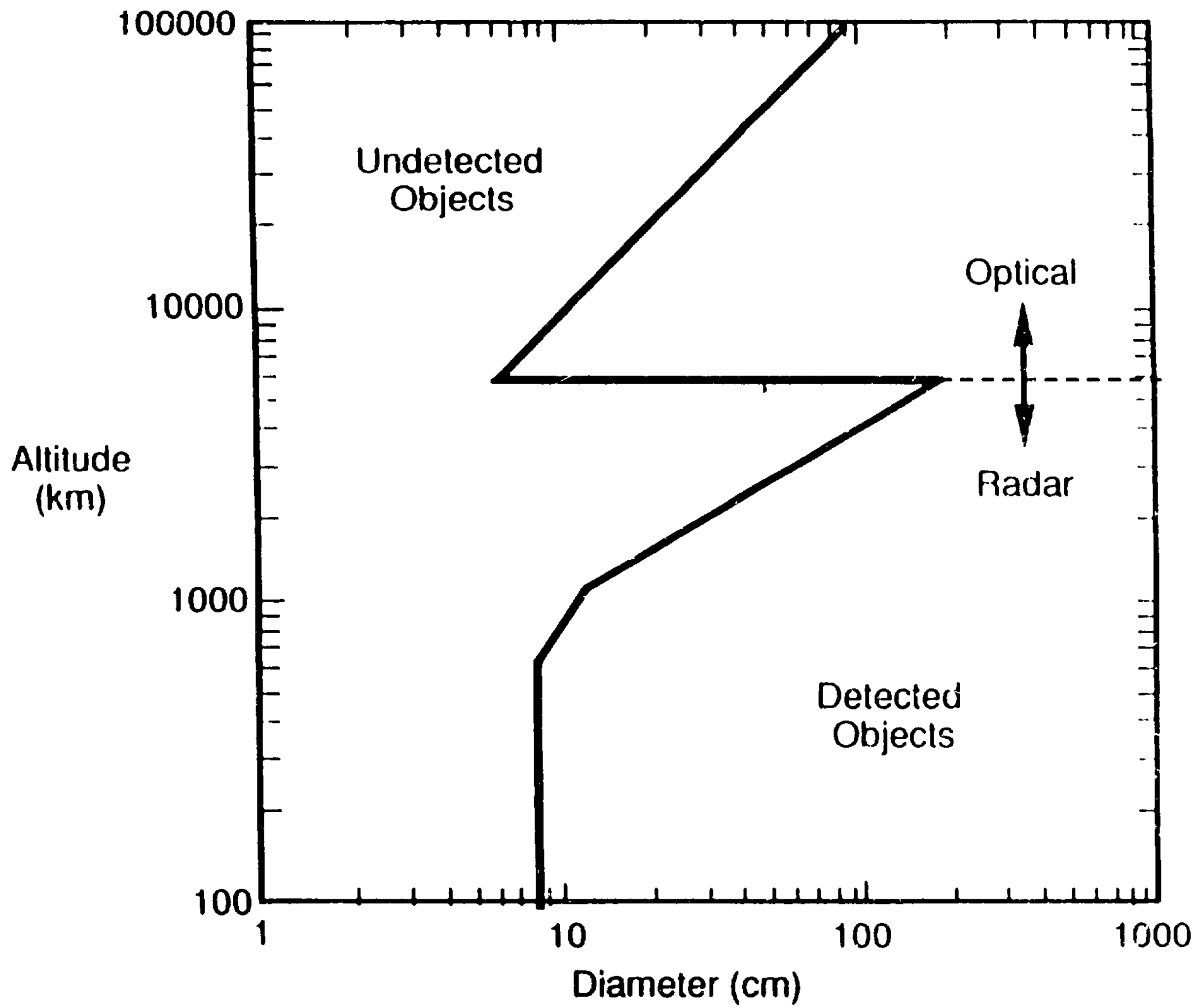
USSPACECOM Cataloged Objects

June 1989



The US Space Command radars can only detect objects larger that about 10 cm, or larger, depending on the altitude. At low altitudes, this limitation is due mostly to the fact that the radars operate at a 70 cm wavelength, which is large compared to the diameter of the debris. A software limitation also limits the debris size to greater that 8 cm. The software limitation is required because the number of uncatalogued objects is too great to catalogue all detected objects with the existing system.

Sensor Altitude Limitations



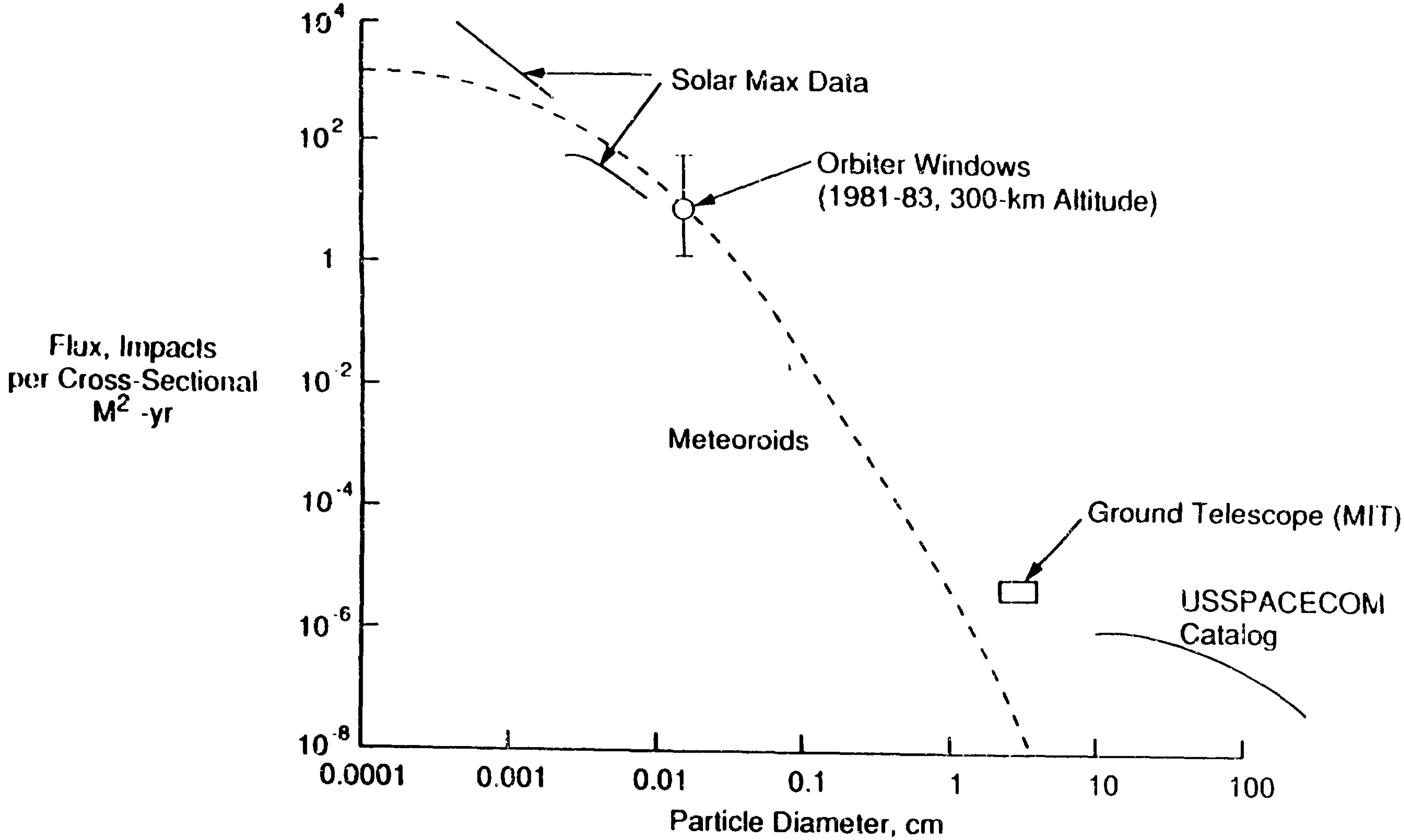
Experiments such as Skylab S149, the examination of the Skylab/Apollo windows, Explorer 46, Examination of the Shuttle window...all indicated an orbital debris population of small objects which were not catalogued.
However, the best data prior to 1989 were the US Space Command Tracked objects, the MIT Telescopic data, and examination of the return Solar Max Satellite surfaces.

MEASUREMENTS USED TO DEVELOP NEW ENVIRONMENT MODEL

- **US Space Command Tracked Data**
  - Catalogued plus analysis data sets
  - Assumed complete to 10 cm
- **MIT Telescopes**
  - Detected 3 to 5 times US Space Command Data predictions
  - Detection theshold 2 cm to 5 cm, as reported by MIT
- **Solar Max Satellite returned surfaces**
  - Both meteoroids and orbital debris detected
  - Detected 0.2 mm and smaller population

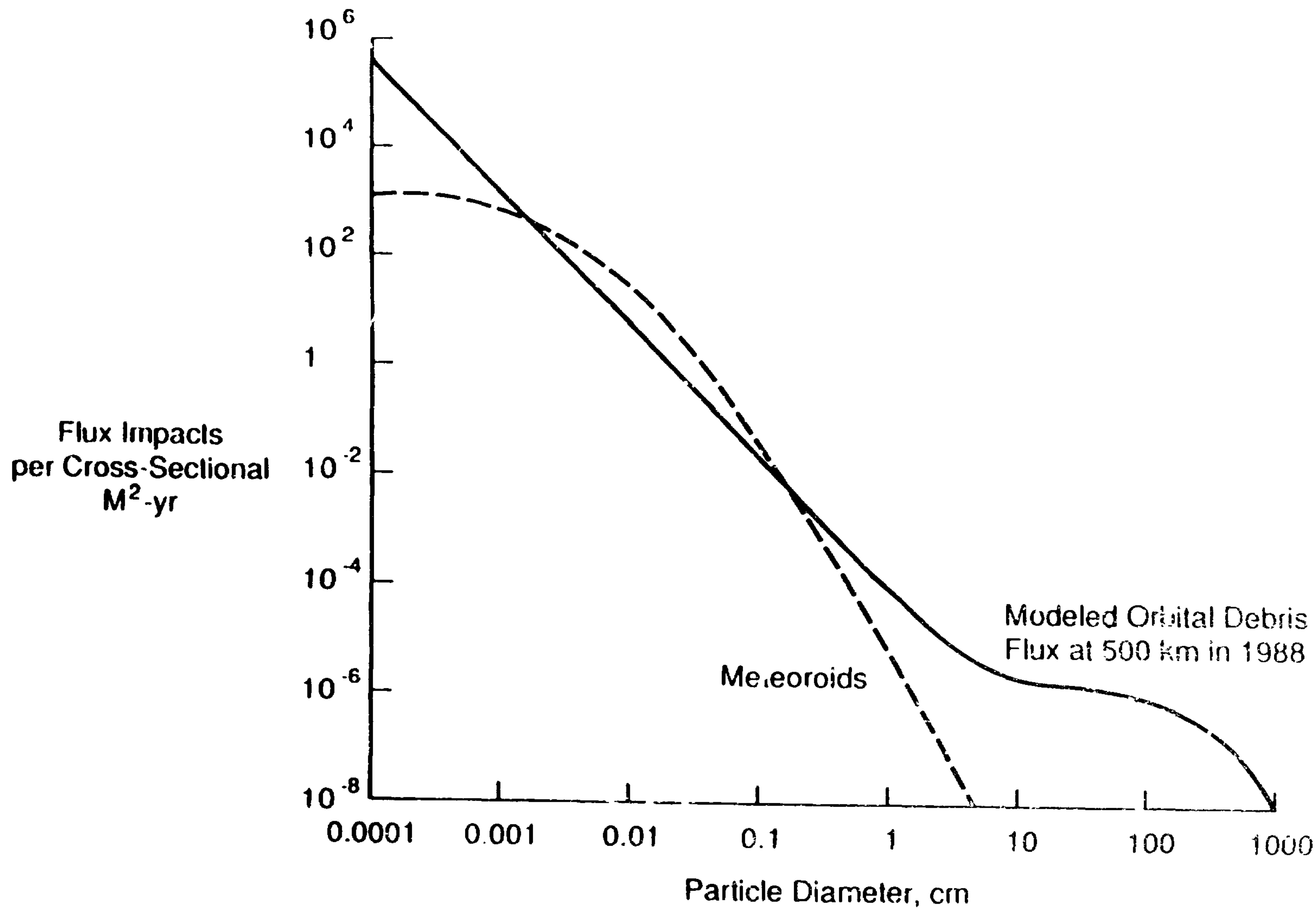
The best orbital debris data is compared with the meteoroid flux. The data indicates that the orbital debris flux is much larger than the meteoroid flux for sizes larger than about 1 cm, and smaller than 0.01 mm.

Summary of Data Sources



A curve was fit through the orbital debris data to obtain an orbital debris flux model at 500 km in 1988. The previous design flux of 1.8E-5 leads to an orbital debris design size of about 1.5 cm, vs. the 0.5 cm meteoroid design size. That is, to design to this debris environment on a 100 sq. meter of surface area to a .9955 probability of no penetration over 10 years will about triple the shielding weight over the meteoroid environment alone.

Modeled Data Sources



A 0.9955 probability of no penetration of a critical element may seem high; however there are many critical elements. With 20 critical elements, a 0.9955 probability of not losing a particular critical element becomes a 0.91 probability of not losing any one of 20 critical elements. If the amount of time is increased from 10 years to 30 years, the probability drops to 0.76. Therefore, reducing these probabilities may not be advisable.

The shielding is likely to be required to defend against something like a 1 cm debris particle. To defend against this size particle, the separation distance between the bumper and the back sheet should be at least 25 particle diameters. This is causing some engineering problems. At a total shield weight of 2.8 gm/cc, expected for a conventional Whipple bumper, the total shielding weight would be 56,000 kgm for 20 elements. While the weight of the shield could be reduced by using more advanced shielding concepts, the size of the debris particle which must be defended against could be larger. In any case, it is likely that the total shielding weight will require extra shuttle flights to place the Space Station into orbit.

Example Shielding/Reliablity for Space Station

Assume 0.9955 probabiltiy of no failure of each critical element for 10 years

- 0.91 Probability of no failure of any one of 20 critical elements in 10 years
- 0.76 Probability of no failure of any one of 20 critical elements in 30 years

Assume each critical element is 100 m surface area, and protected against 1 cm projectile at 10km/sec., using conventional aluminum bumper.

- Optimal shield requires at least 25cm separation
- Shield weight approximately 56,000kgm for 20 elements

Understanding the environment has some critical weight issues associated with the Space Station. In 1989, three tests were performed to test the model environment. These tests used the Arecibo Radar in Puerto Rico, the Goldstone Radar in California, and US Space Command's GEODSS telescopes located both a Diego Garcia and Maui, Hawaii. The largest surprise came from the telescopic data which indicated that there are two to three times as many objects in orbit to a limiting size of 10 cm than indicated by the catalogue.

1989 TESTS TO NEW ENVIRONMENT MODEL

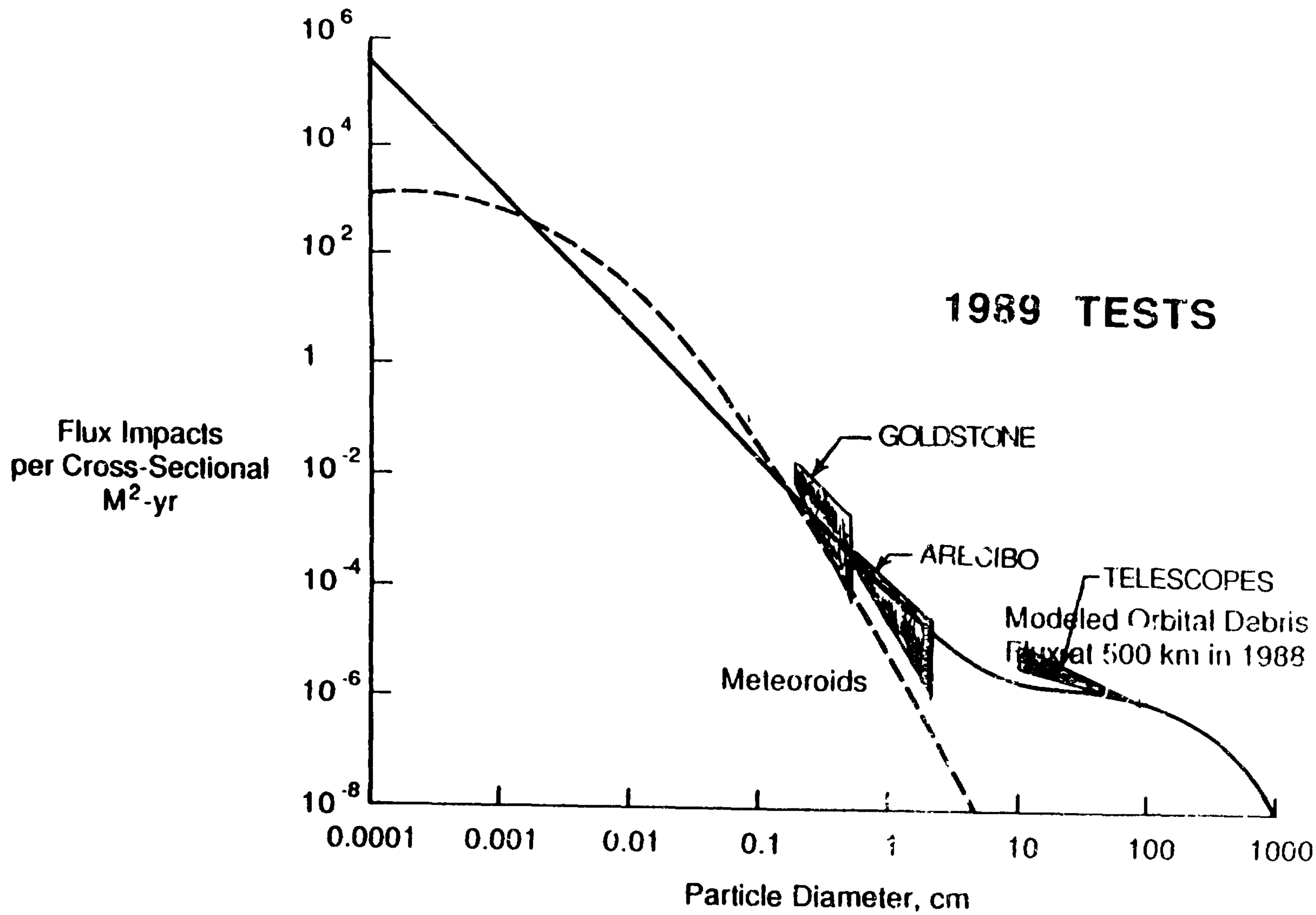
- Arecibo Radar
  - 18 hours observation
  - 12.6cm radar wavelength
  - 0.5cm to 2cm debris detected
  - Agreed with model within uncertainty of data

- Goldstone Radar
  - 14.5 hours observation
  - 3.5cm radar wavelength
  - 0.2cm to 0.5cm debris setected
  - Agreed with model within uncertainty of data

- US Space Command Telescopes (GEODSS)
  - More than 20 hours analyzed
  - Larger than 10cm debris detected
  - Model too low for sizes between 10cm and 1 meter
  - Model maybe too low for sizes between 2cm and 10cm.

Within the errors of measurements, the two radar experiments agreed with the model environment; however, the telescopic data indicates that the model is too low for sizes larger than 10 cm, any possibly too low for sizes between 2 cm and 10 cm. However, we still do not have any good measurements of debris between 1 cm and 10 cm.

Modeled Data Sources



To collect data on debris sizes between 1 and 10 cm, we have an agreement with US Space Command, where they will collect data using their Haystack radar and build and operate an Auxiliary radar. In exchange, NASA will pay for the construction of the Auxiliary radar. These two radars will have sufficient data by 1992 to update the environment model, if necessary, in time for CDR's.

Long term debris monitoring is planned by GBR-X, a large, X-Band radar planned to be constructed nearer the equator on Kwajalein.

12/5/89

ORBITAL DEBRIS RADAR PROGRAM
CURRENT STATUS

- U.S. DEPARTMENT OF DEFENSE SUGGESTED ALTERNATIVE TO DEDICATED ORBITAL DEBRIS RADAR

- NEAR-TERM DATA COLLECTION

  - HAYSTACK

    X-BAND; 10 GHz
    0.05° BEAMWIDTH
    400 KW PEAK POWER
    1 - 5 MSEC. PULSE; UP TO 50% DUTY CYCLE
    1 CM. DIAMETER AT 500 KM ALTITUDE
    10° ELEVATION ANGLE TO REACH 28° ORBITS WITH 1700 KM SLANT RANGE

  - HAYSTACK AUXILIARY

    Ku-BAND; 16.7 GHz
    0.15° - 0.3° BEAMWIDTH
    100 KW PEAK POWER
    0.25 - 5 MSEC. PULSE; UP TO 30% DUTY CYCLE
    1 CM. DIAMETER AT 500 KM RANGE
    VERTICAL STARING; ONLY ABLE TO REACH 42° ORBITS

Projecting the future environment is very difficult. Already changes in operational practices are likely to reduce the number of satellite breakups in the immediate future; if so, the current projections should be reduced. However within the next 10 to 20 years, random collisions between non-operational satellites are likely to cause the breakup rate to again increase. If so, the long term environment could increase faster than the model projections.

Projecting Future Environment

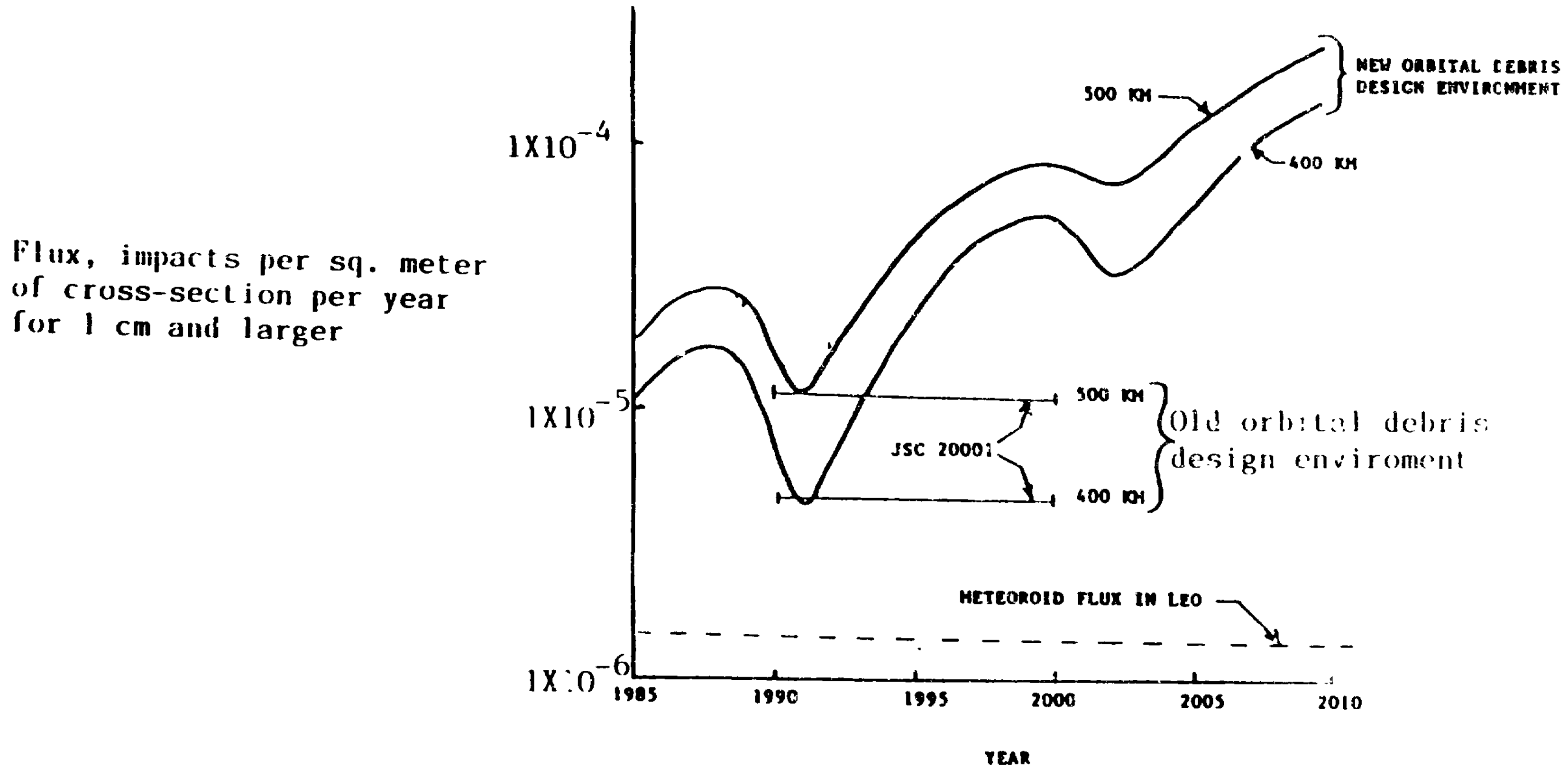
- Must assume debris sources, solar activity
  - Traffic models (increase launch rate?)
  - Satellite fragmentation rates
    - Future accidental explosions? Type?
    - Military test?
    - Random collision fragmentation tied to traffic model
  - Unmodeled sources?
  - Solar activity not always as predicted
- Current model assumption
  - Accumulation of large debris continues 5% increase per year (near term)
    - World launch rate does not significantly increase
    - Accidental, intentional fragmentation remains constant (5 per year)
    - Random collision fragmentation increases
  - Accumulation of small debris increases at 10% per year
    - Expected from random collisions within few years
    - May cover unmodeled sources within immediate future
  - "Average" solar cycles after next cycle

NASA

The new environment is time dependant, and changes with solar activity. The new and old models are only in agreement near the maximum of the current solar cycle. The high values and large uncertainty in this projection increases the problem of shielding the Space Station.

New Orbital Debris Design Environment

Example Outpu. for 1 cm and Larger Orbital Debris



- Compared to JSC 20001
- Compared to Meteoroid Environment
- Inputs Assume
  - Nominal Traffic Model
  - Expected Solar Activity

There is uncertainty in both the current and projected environment. In addition, there is an uncertainty in the consequences of the environment (e.g., how critical is a penetration into a critical element?). The Space Station design must be able to accommodate to these uncertainties and respond to new data as the uncertainties are reduced. One way of doing this is to build the Space Station so that all critical elements are protected to some level, and are designed such that new protection can be added, if necessary. Shielding alone may not be practical; collision warning, doors that close automatically, selective heavily shielded areas, and other techniques may be required to obtained the desired level of safety. The Space Station design should not exclude these possibilities.

SUMMARY

- Current Environment is uncertain
  - Best Estimate contained in TM 100-471 (new environment)
  - Improved Environment Model expected before CDR's
    - MIT Haystack, Haystack Auxiliary radars
    - LDEF
    - Experiments with Eglin, Goldstone radars and Ground telescopes
- Future Environment is uncertain
  - Planned Traffic Models show long-term increases in population
  - Changes in operational practices could result in short-term decreases
    - US, ESA, Japan already making changes
    - Discussions with USSR
  - Environment will be monitored by GBRX, Space Station Cosmic Dust Facility, Future experiments
- Space Station design requirements should
  - Meet short-term safety and maintaince needs
  - Respond to increased knowledge of the environment and vulnerablilty to the environment

N93-27839

An Evolutionary Construction Facility for Space Station Freedom

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Technology for Space Station Evolution - A Workshop
Dallas, Texas

January 16-19, 1990

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Space Station Freedom

Space Station Freedom (SSF) will support permanent human presence in space and has the potential to enable scientific and exploratory endeavors unequalled in history. Most importantly, it will permit the use of human abilities and interaction to perform tasks, interpret results, and react to contingencies in real time. With larger and more ambitious spacecraft being developed, it will serve as a site for construction, checkout and deployment. However, with the realities of government funding, the Space Station Freedom configuration has been cut back to the point where there is little "real estate" left for scientific instruments, and even less for the development and demonstration of the technologies required for in-space construction.

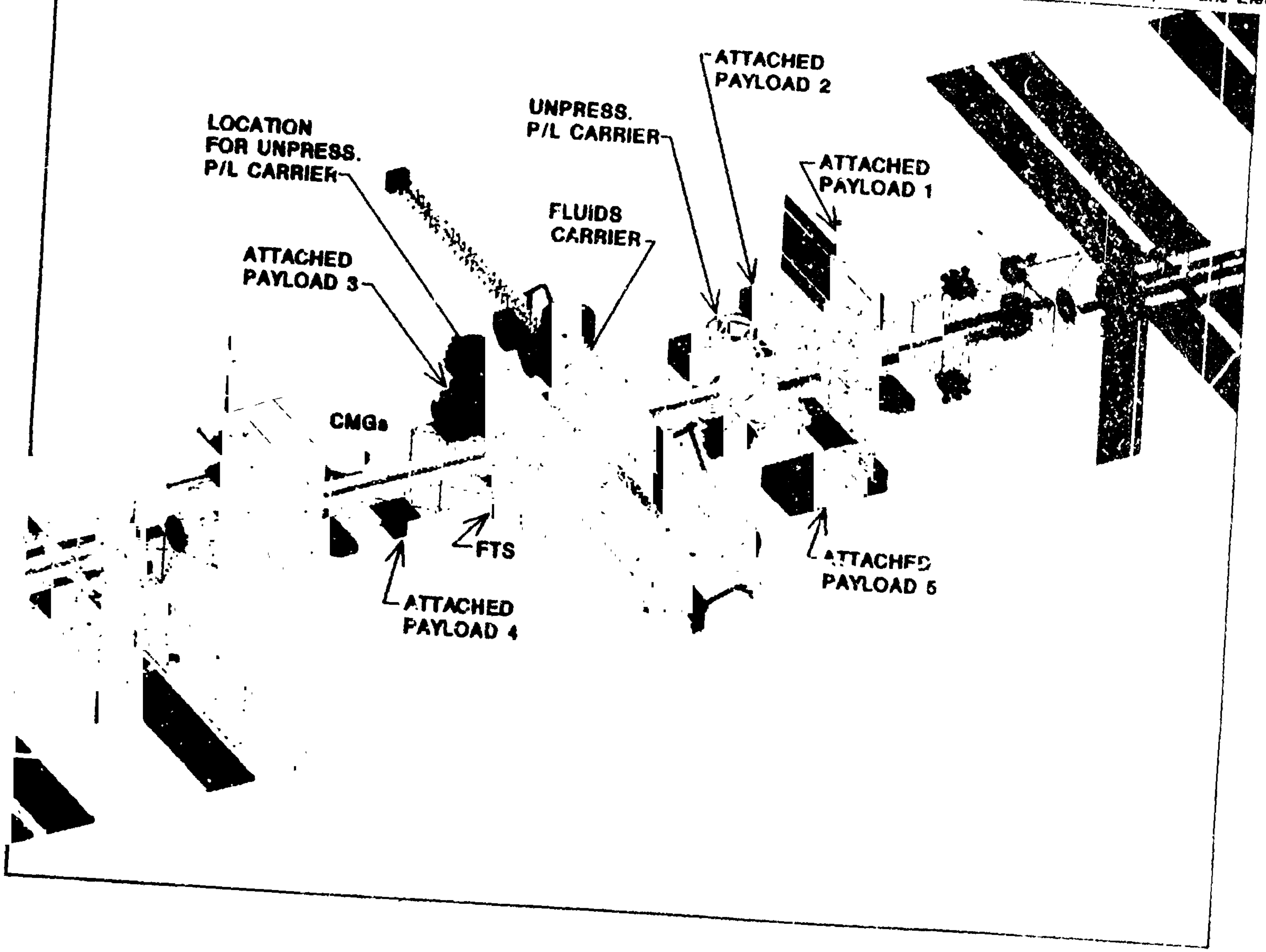
While it is true that the construction of Space Station Freedom itself will provide valuable experience in some of the techniques necessary for in-space construction, a facility attached to SSF is required to develop and demonstrate the techniques that will enable on-orbit construction of future large spacecraft.

Examples of attached scientific experiments that currently envision in-space construction are: Solar X-Ray Pinhole Occulter Facility, Astromag, and X-Ray Large Array. Examples of large assemblable spacecraft are: Large Deployable Reflector (LDR), Geostationary Platforms, and interplanetary vehicles. Future additions to SSF such as satellite and OTV servicing hangers and solar dynamic power systems will also need to be constructed in space.

Aerospace Systems Technologies

Space Station Freedom

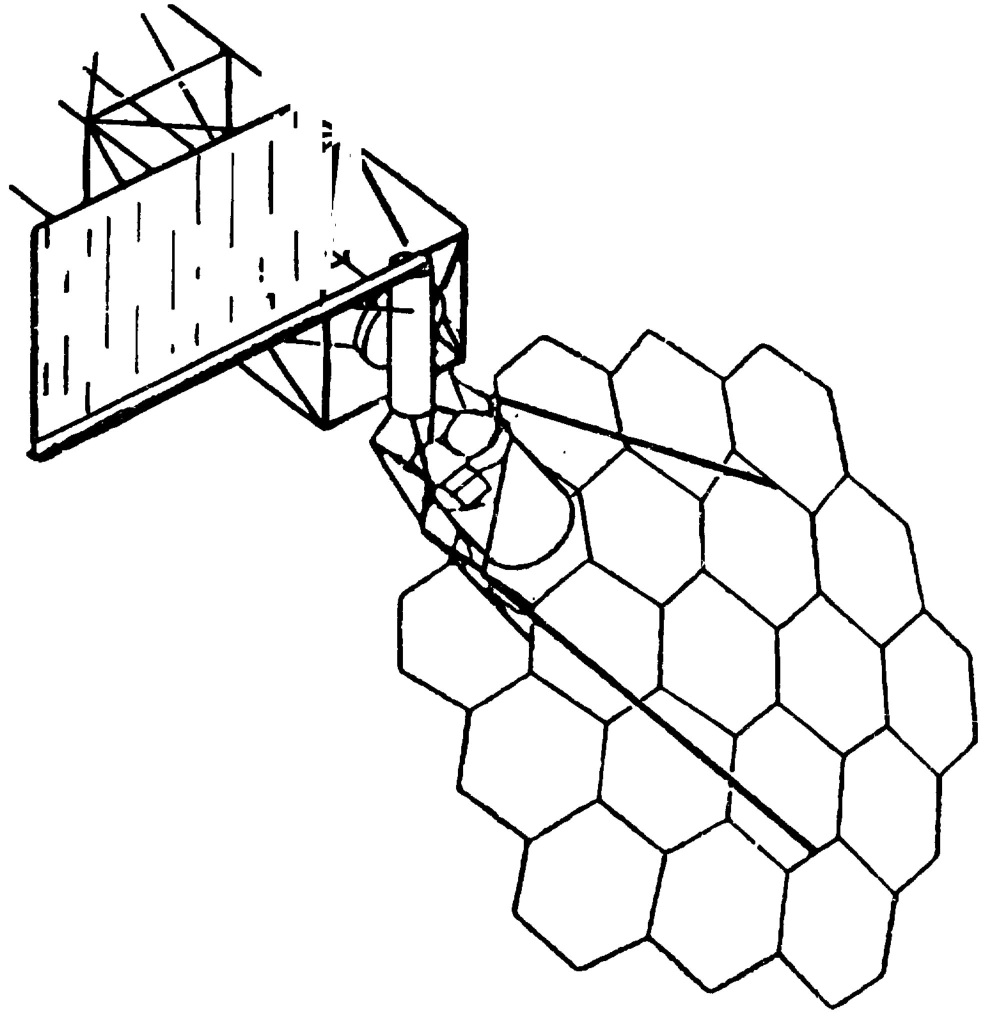
Boeing Aerospace and Electronics



Solar Dynamic Power System

Future growth of Space Station Freedom will use many of the same techniques of construction used for the initial configuration. The addition of solar dynamic power, however will require new techniques because of the use of segmented reflector segments that must be precisely aligned to focus the Sun's energy on the collector. Construction will probably take place near the module cluster to minimize the distance that the individual components must travel during assembly. The complete system will then be transported to its operational position at the end of the power boom.

Solar Dynamic Power System

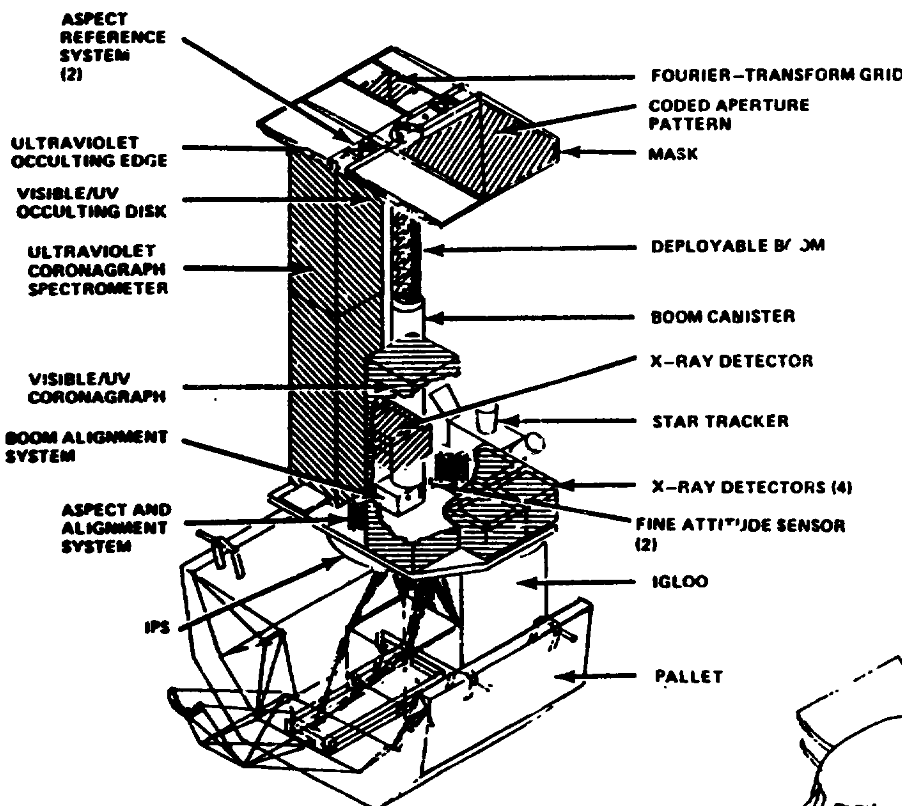


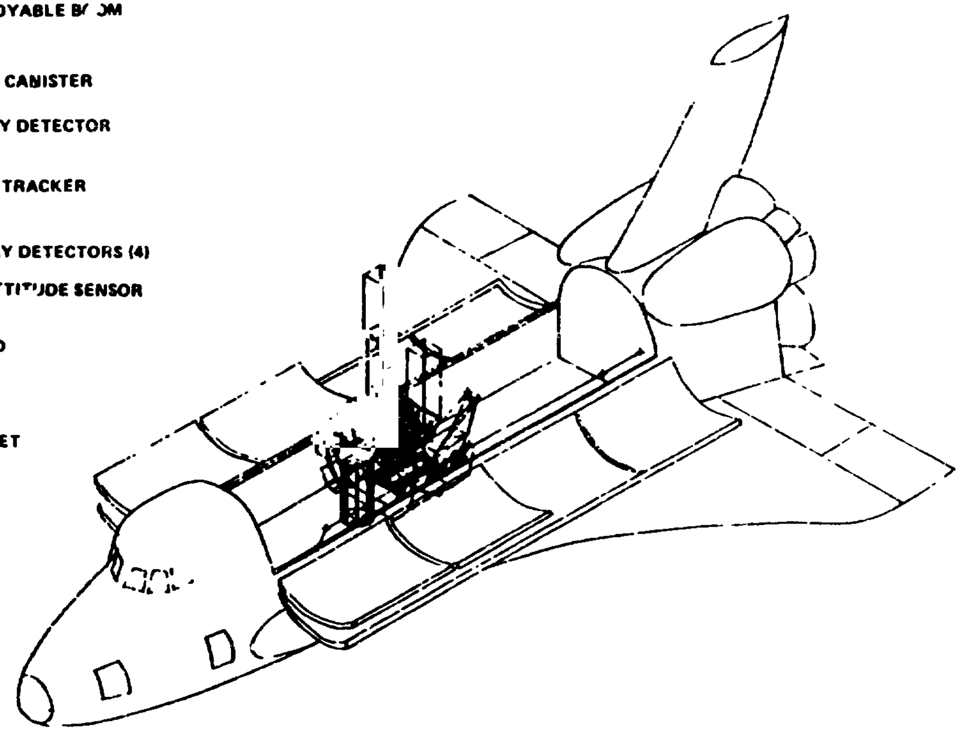
Solar X-Ray Pinhole Occulter Facility

Although it is designed as a Shuttle experiment, the Solar X-Ray Pinhole Occulter Facility is envisioned as being placed on SSF for long duration operation. As designed, it is an automatically deployed experiment and requires little or no human interaction. Since it must face the Sun, its operational location will be on the space viewing side of SSF.

Solar X-Ray Pinhole Occulter Facility (SPOF)

PINHOLE OCCULTER FACILITY
PHASE A CONCEPT





Astromag

The Astromag experiment is an attached experiment whose modules must be assembled in space. It is a space-facing experiment that incorporates a strong superconducting magnet and, therefore, must be separated from SSF by 10-15 meters (two or three truss bays) to minimize its interference with SSF systems. It will most likely be assembled at its operational site on the outward-facing surface of SSF.

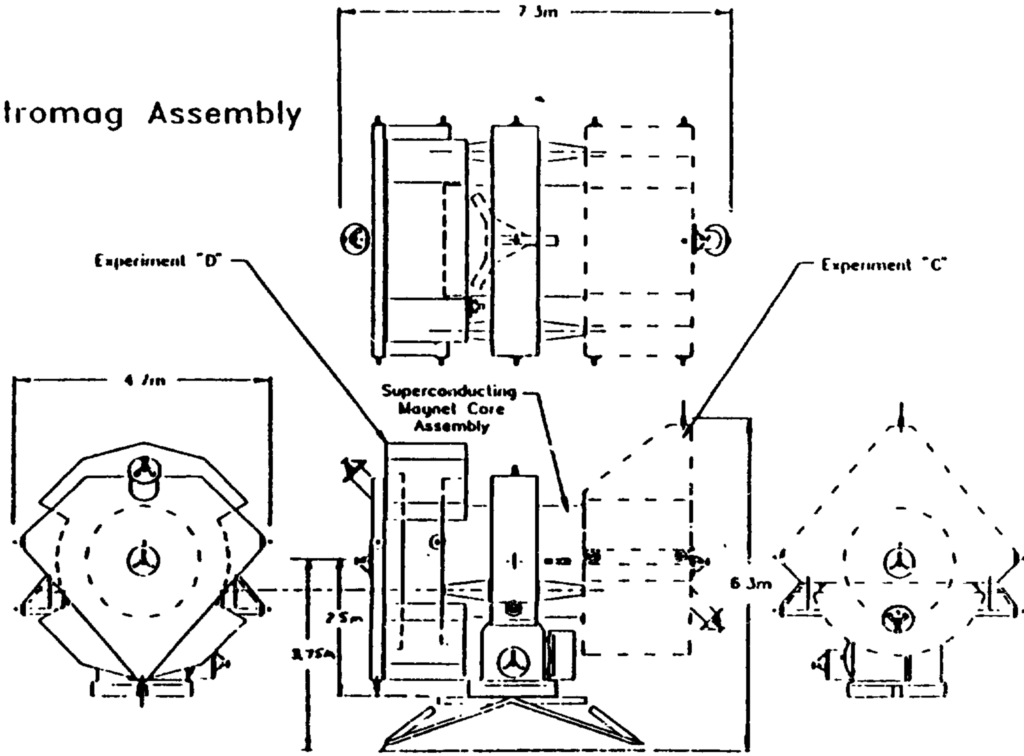
Aerospace Systems Technologies

Astromag

Boeing Aerospace and Electronics

ASTROMAG CONFIGURATION

Astromag Assembly

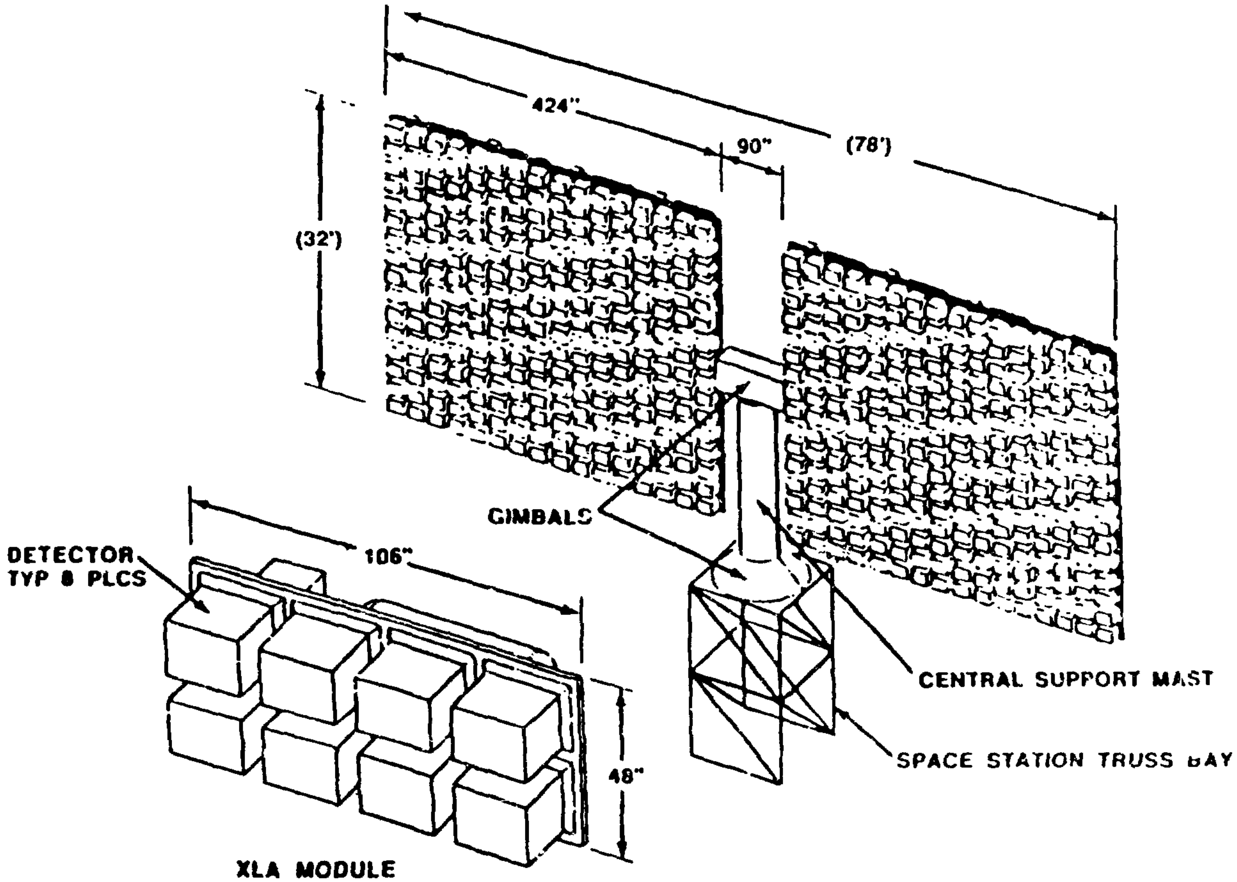


X-Ray Large Array (XLA)

The X-Ray Large Array experiment is characterized by a pair of large planar arrays assembled from 64 individual detector modules. They are mounted to a central support mast and are pointed at a target in space by two gimbals. Its preferred operational location is also on the outward-facing surface of SSF.

X-Ray Large Array (XLA)

XLA BASELINE CONFIGURATION

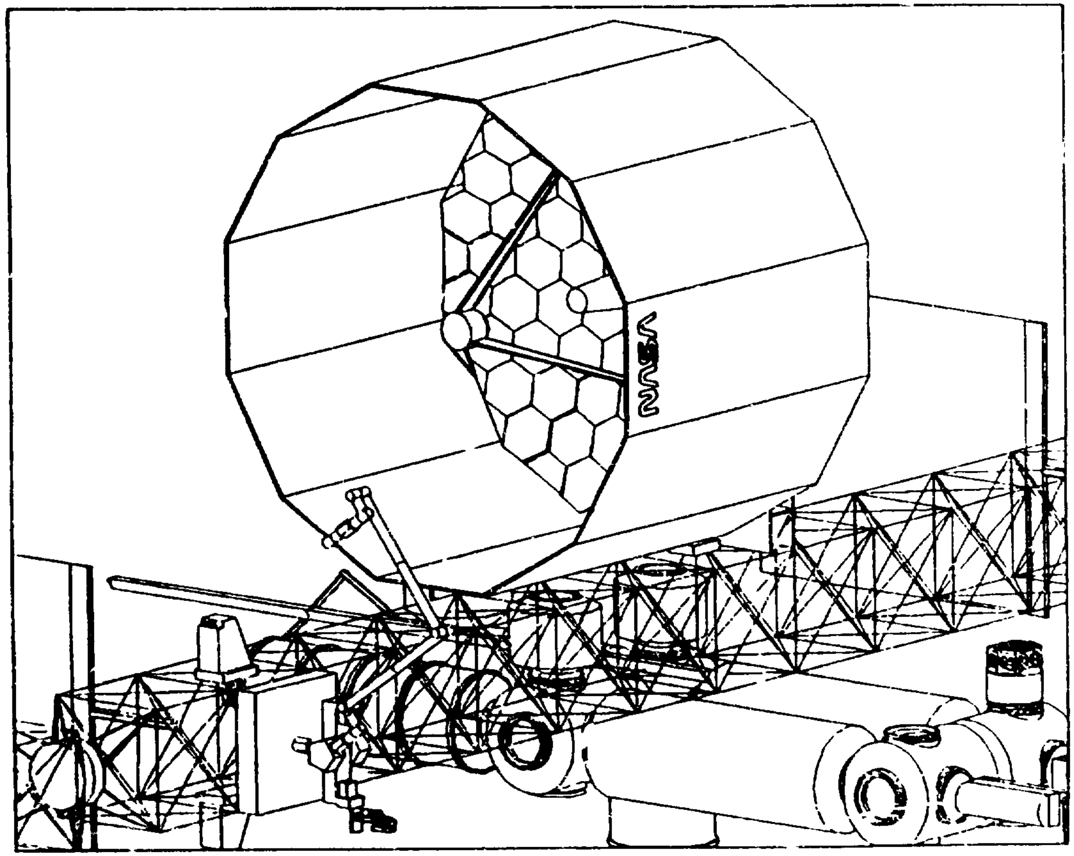


XLA MODULE

Large Deployable Reflector (LDR)

Precision segmented reflector technology is exemplified by the LDR, a 20 meter diameter, segmented optics, submillimeter telescope. Its size and dimensional precision make on-orbit construction necessary. The proposed construction scenario has been well documented by JPL. It is assembled piece by piece by EVA astronauts with SSF mobile service center (MSC) assistance. Its required orientation relative to SSF is shown in the figure. This is to prevent direct sunlight from striking the reflector surface during construction. Once assembled, it is separated from SCF and transported to its operational orbit.

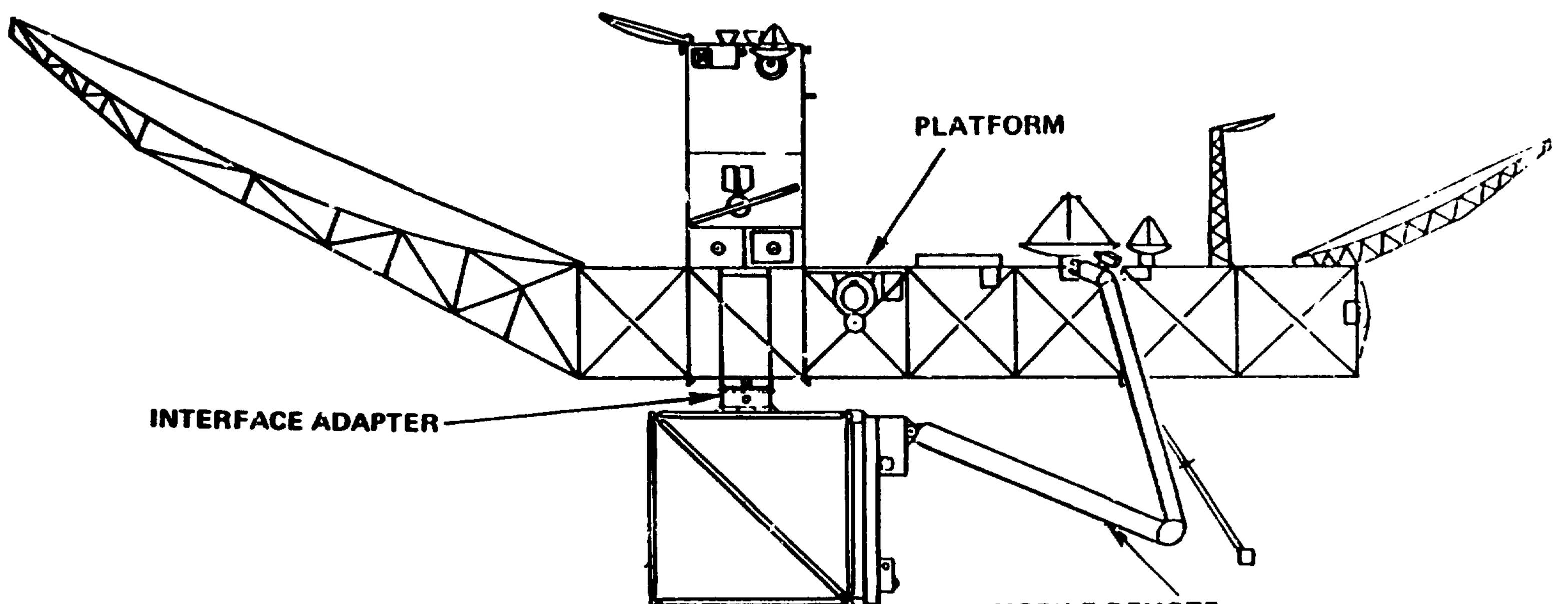
Large Deployable Reflector (LDR)



Geostationary Platform System

The Geo Platform System shown in the figure consists of a backbone truss structure to which are attached two reflector systems and other experiment modules. During construction, it is attached to SSF using an interface adapter. There are apparently no restrictions on its orientation during assembly. Following assembly, it is transported to geosynchronous orbit.

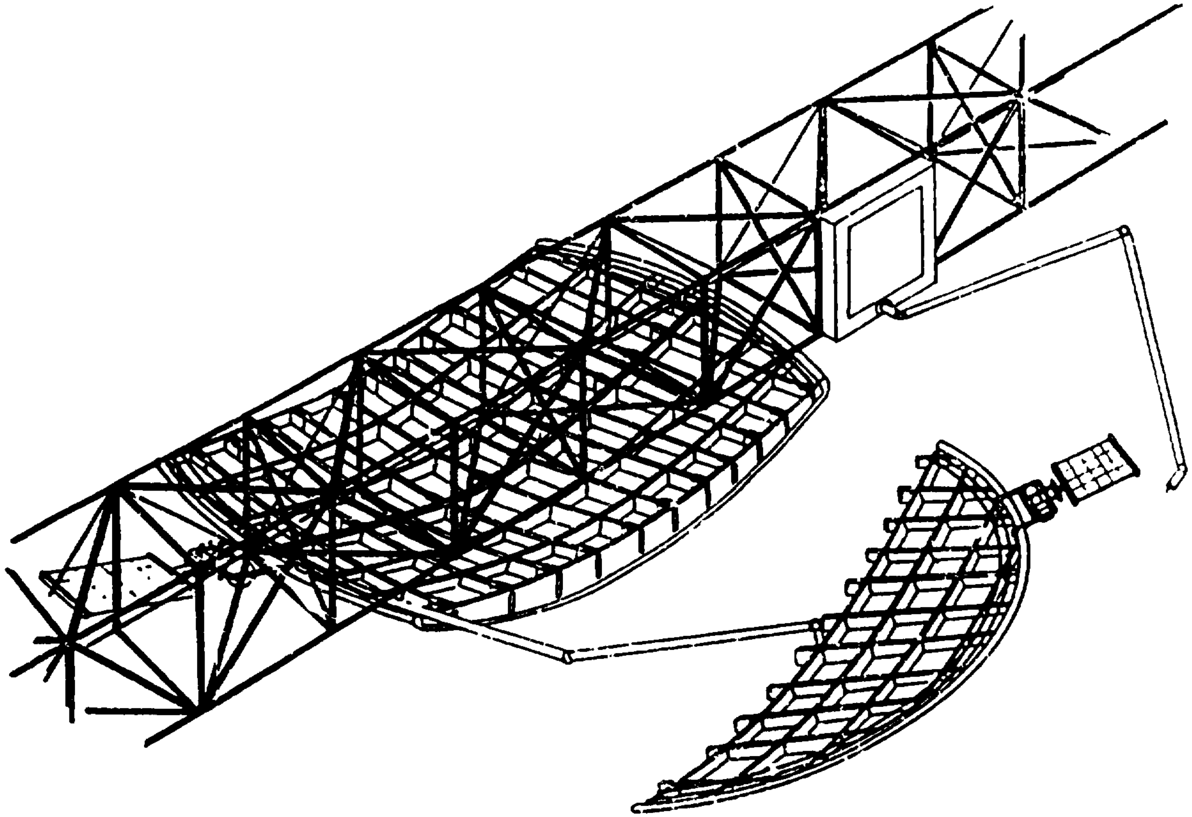
Geostationary Platform System



Interplanetary Vehicles (Pathfinder Program)

Looking into the future, interplanetary missions to explore the solar system will require very large spacecraft that must by assembled in space. NASA's Pathfinder Program is identifying and advancing the technologies and capabilities necessary to enable these missions. This figure shows a possible assembly method for a large aerobrake used on a spacecraft designed for a manned Mars exploration mission.

Interplanetary Vehicles (Pathfinder Program)



Mars Exploration Mission Configuration, Assembly of the Aerobrake Sections at Space Station

Construction Facility Requirements

Attachment location - Neither the facility or its construction projects should interfere with SSF systems. Obstruction of line-of-sight to SSF components should be minimized. Construction projects should be within sight of the habitable modules. For safety, all EVAs must be observable by an IVA crew member.

Project orientation - Both the facility and the construction projects should be oriented to minimize drag. The facility should provide required project orientation (e.g., sun avoidance)

Attachment method - The facility should allow flexibility in the method for project attachment. For example, an axisymmetric structure could be attached at a single point, while a long structure may require multiple attach points, and a large diameter wheel-like structure could be attached at its rim.

Positioning - Construction projects can be assembled by moving them past a fixed work station, or by using a portable work station to access all areas of the project.

Construction aids - Generic tools, fixtures and assembly aids should be provided by SSF while unique equipment must be provided by the project. Examples of SSF-provided aids are: lights; tools and tool containment devices; portable astronaut positioning systems, foot restraints, lifelines and tethers; adjustable structural supports, hold-downs, braces and attachment devices; video monitoring equipment and supports; portable measurement devices and instrumentation; and generic test and checkout equipment.

Equipment storage - A central enclosed storage location for the above equipment inventory should be provided. The storage area should also provide temporary storage for small components awaiting assembly, particularly those that need to be protected from the harsh space environment. A storage platform for temporary storage of larger components should also be provided at the construction facility.

Utilities - Electrical power and data lines are required by the construction facility and, in some cases, by the construction project. Some ssemblable satellites may also require thermal control until their on-board thermal control systems are activated.

Test and checkout equipment - Generic instruments and measurement devices for structural alignment and for thermal, electrical, and dynamic measurements should be provided by SSF.

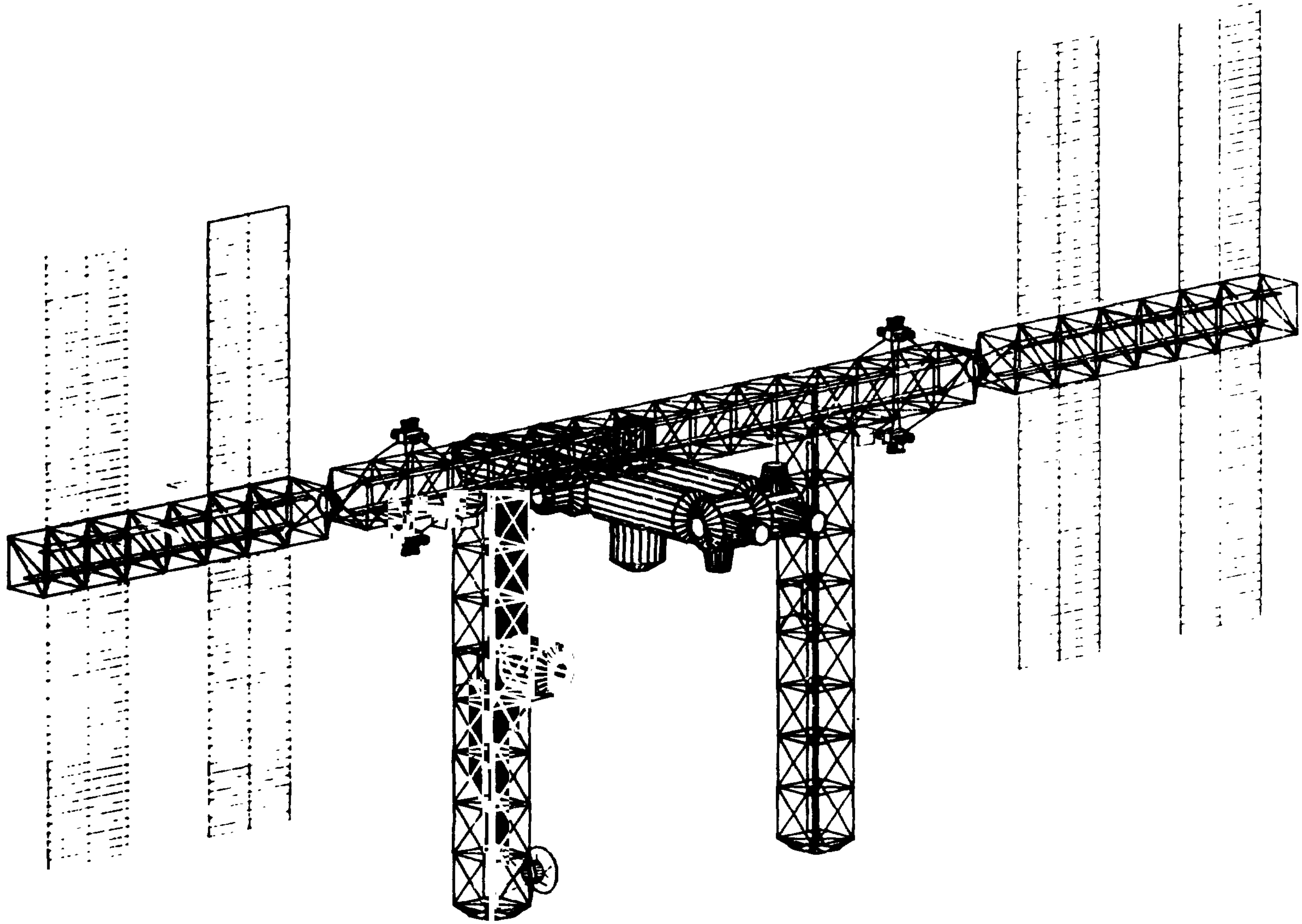
Construction Facility Requirements

- Attachment location
  - Non-interference with SSF systems
  - Observation of EVA by IVA crew
- Project orientation
  - Minimize drag
  - Sun avoidance
- Attachment method
  - Single point
  - Multiple attachments
- Positioning
  - Translation or rotation
  - Fixed or portable work station
- Construction aids
  - Tools, fixtures, lights, assembly aids
- Equipment storage
  - Internal and external
- Utilities
  - Electrical power, data, thermal
- Test and checkout equipment
  - Alignment, temperature, electrical measurement, modal survey

Experiment/Construction Facility Concept

The proposed construction facility concept is shown in this figure. It consists of two 8-bay portions of the lower keel structure. These truss beams provide sufficient facilities for many construction projects currently envisioned and, at the same time, promotes SSF evolution. The facility includes several Structural Interface Adapters (SIAs), generic storage platforms, a storage module, a turntable, and, not shown in the figure, a surrogate payload bay and a portable work station. Utility trays are included to provide electrical power and data lines.

Experiment/Construction Facility Concept

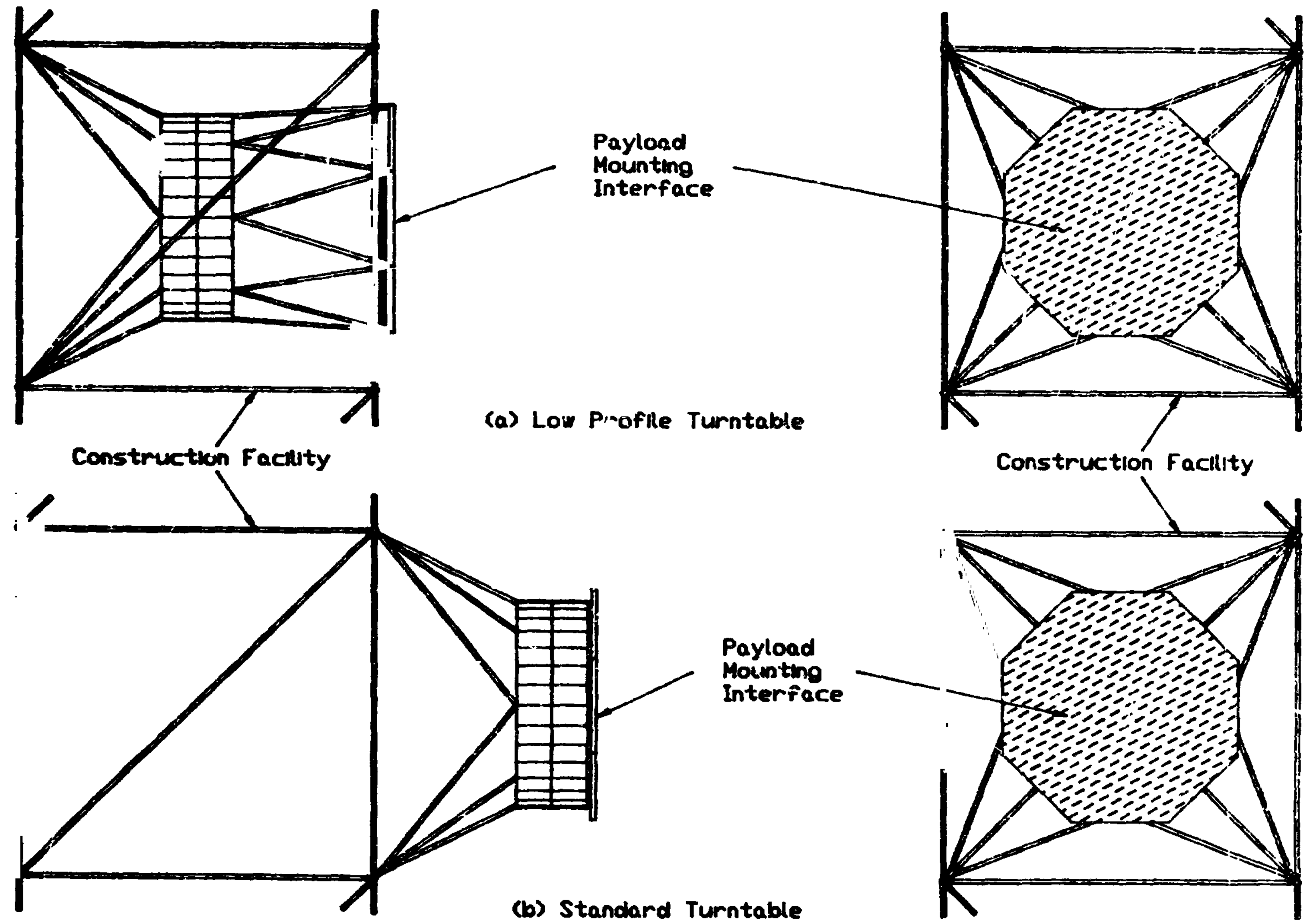


Turntable Concepts

A turntable allows attachment of a construction project or payload at a single location, and rotates to provide access to all sides.

The turntable concept shown is a modified alpha joint attached to the construction facility truss. The standard turntable is attached to the truss externally, in the same manner that the alpha joint is attached to the main power boom. If more volume is required for a large construction project, the turntable can be attached within the truss cube after removing a truss diagonal member and attaching an adapter truss. The use of the SSF alpha joint design supports commonality and provides the required electrical and data path across the interface. Its structural capability is also sufficient for large construction projects.

Turntable Concepts



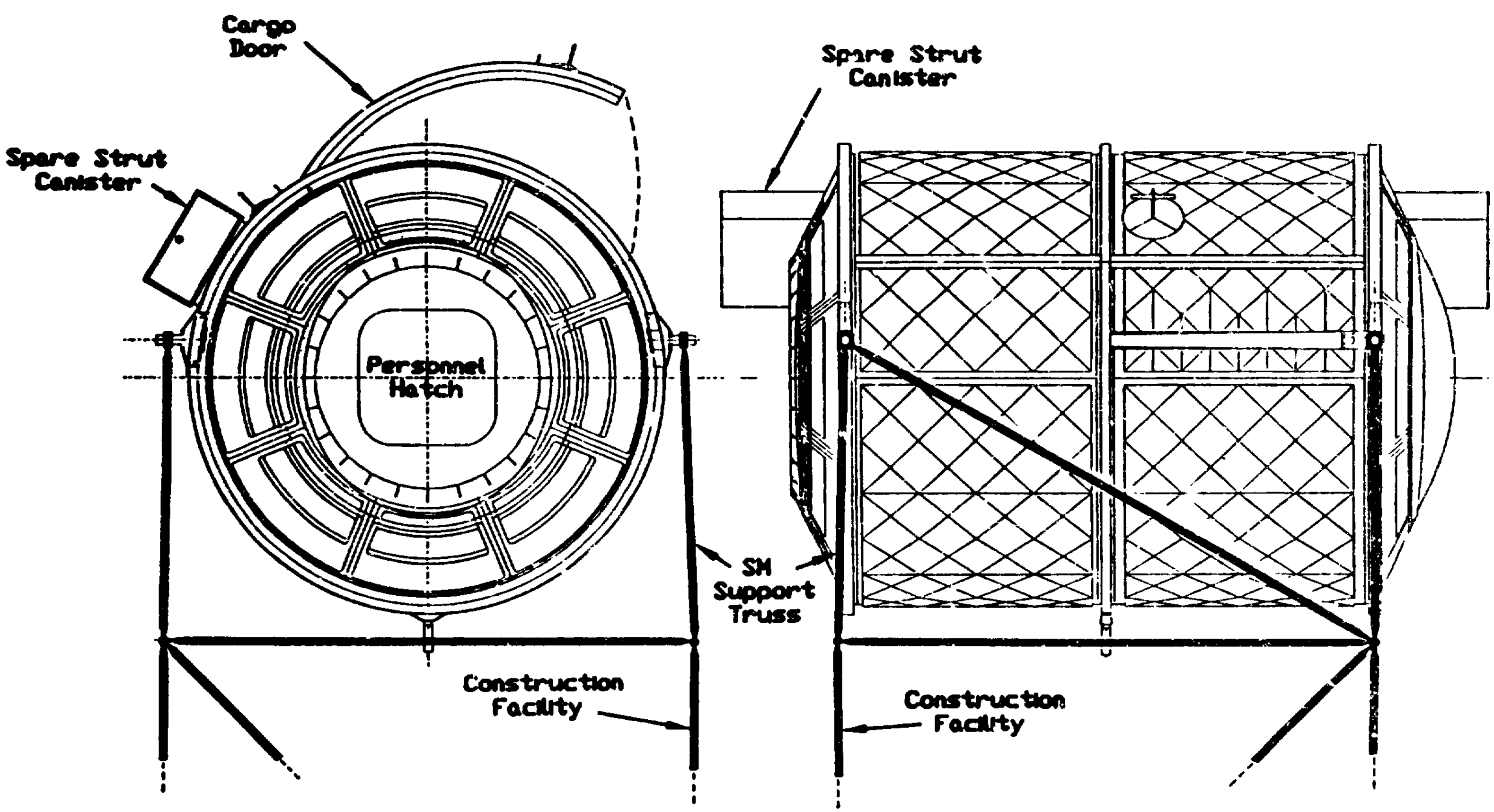
(a) Low Profile Turntable

(b) Standard Turntable

Storage Module (SM)

The proposed storage module design is a modified Logistics Module (LM). Its exterior shell structure is identical with the LM with two exceptions. First, an electrically operated cargo door is built into the side to allow large components to be stored and retrieved by the MSC. Since the storage module is not required to be pressurized, the cargo door does not need to be pressure tight. The second exception is the addition of attachment devices for a canister that contains spare SSF truss struts and nodes. The personnel hatch is retained to allow crew access without opening the large cargo door. The interior structure is modified to permit the storage of tools and other generic construction aids and instruments. It is attached to the construction facility using truss members that connect to its trunion and keel fitting pins.

Storage Module (SM)

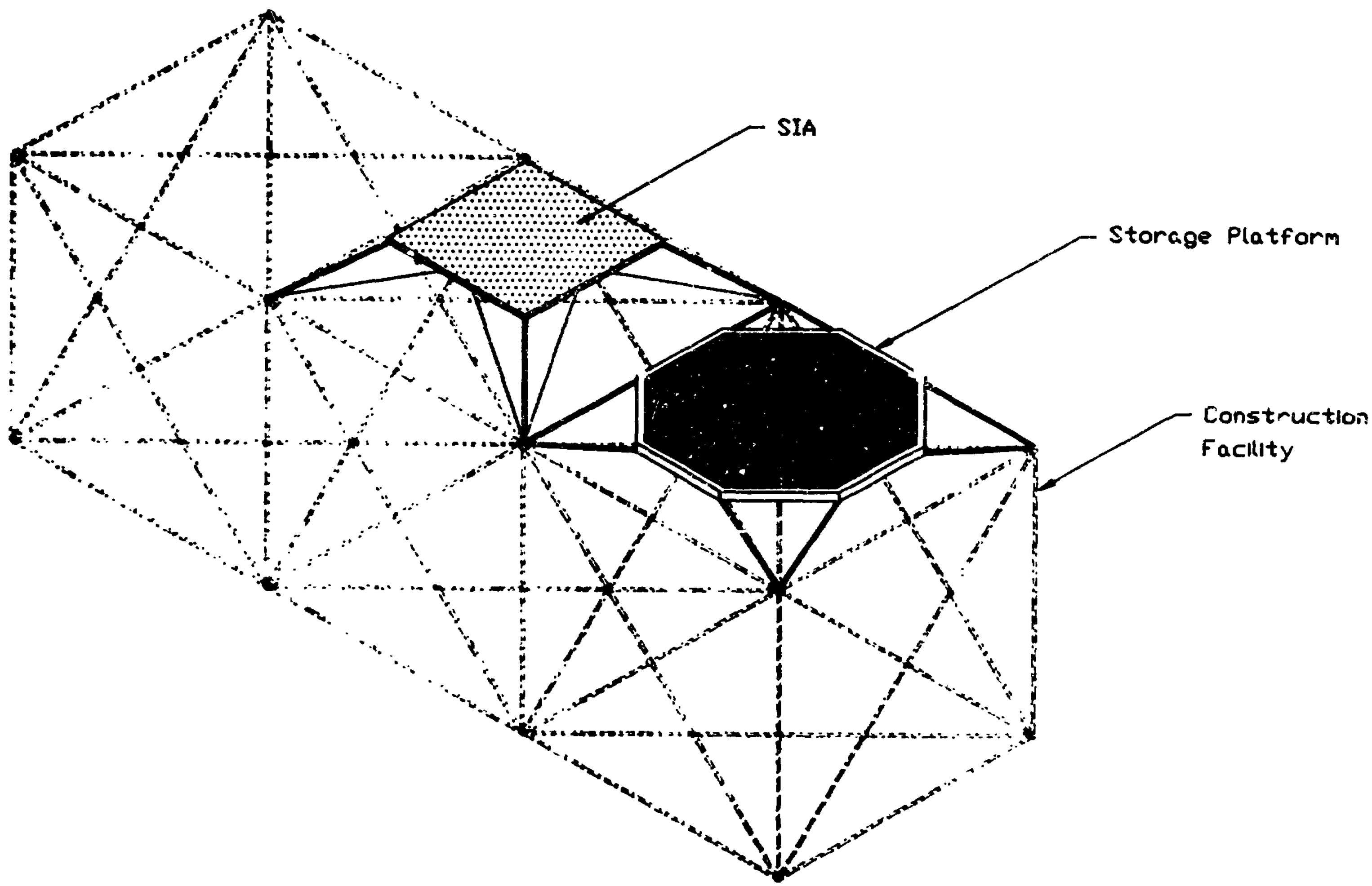


Generic Attachment Platforms

Attached Payload Attachment Equipment (APAE) that provide a generic attachment method for experiments will be provided by SSF. It consists of a structural interface adapter (SIA) that is attached to the SSF truss. A corresponding payload interface adapter (PIA) is attached to a payload. The APAE provides a physical, electrical and thermal interface with attached payloads. The construction facility will include several SIAs that can be used when needed.

A more generic storage platform is also proposed for the temporary storage of parts, equipment, containers and components awaiting assembly. It is an octagonal platform attached to the construction facility truss nodes that does not provide electrical or thermal interfaces. Its surface is a gridwork that will accommodate a generic tie-down mechanism that can easily be placed at any location on the grid. Containers or components can be restrained to these tie-down fixtures.

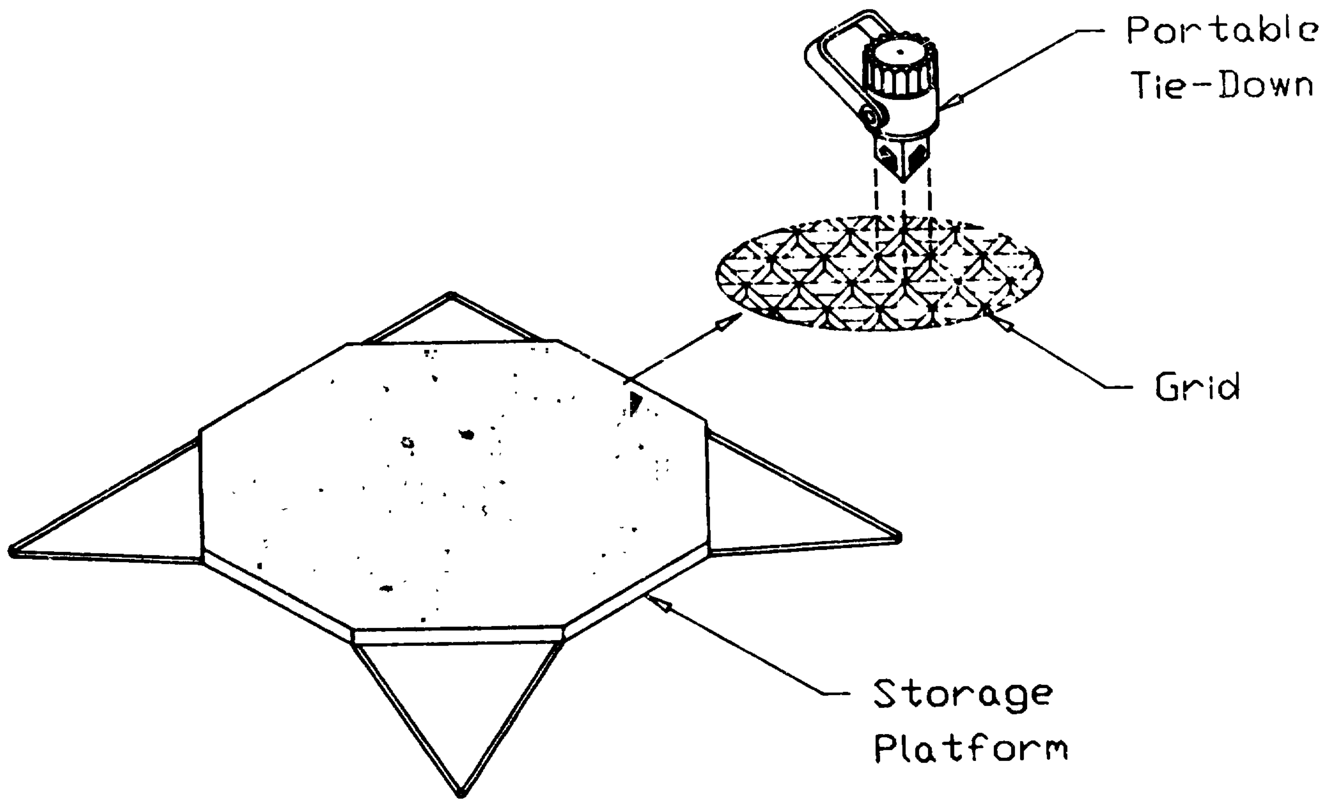
Generic Attachment Platforms



Storage Platform Concept

This figure shows more details of the platform, its gridwork surface and the protable tie-down mechanism. The grid can be either triangular, as shown, or square. The tie-down fixture has spring-loaded latches that firmly restrain the fixture when placed into one of the grid openings. The handle, attached to a rotating collar, can rotate about two axes, and is the attachment point for tie-down straps or other mechanisms. The fixture is easily released by an EVA crew member by turning the knob within the handle (after it is rotated out of the way). This releases the latches, and the fixture can be pulled out of the grid.

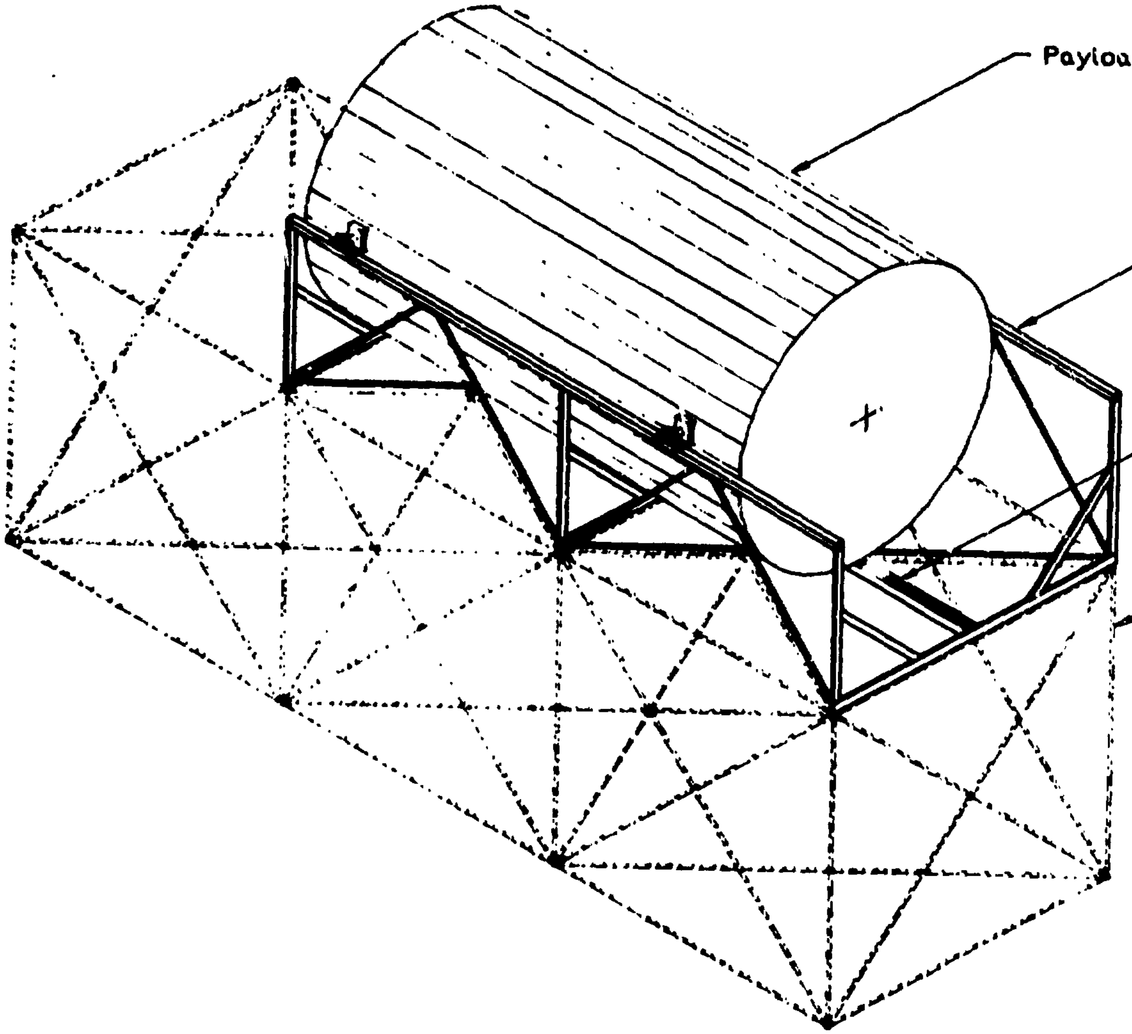
Storage Platform Concept



Surrogate Payload Bay

It may be necessary to accommodate large payloads and shipping containers that are tied directly to the Orbiter longerons via trunion and keel pins. The surrogate payload bay facility duplicates the geometry of the STS payload bay and includes adjustable longercn and keel trunion fittings. It can also supply the same utilities (electrical, thermal, etc.) that are supplied by the Orbiter, if required.

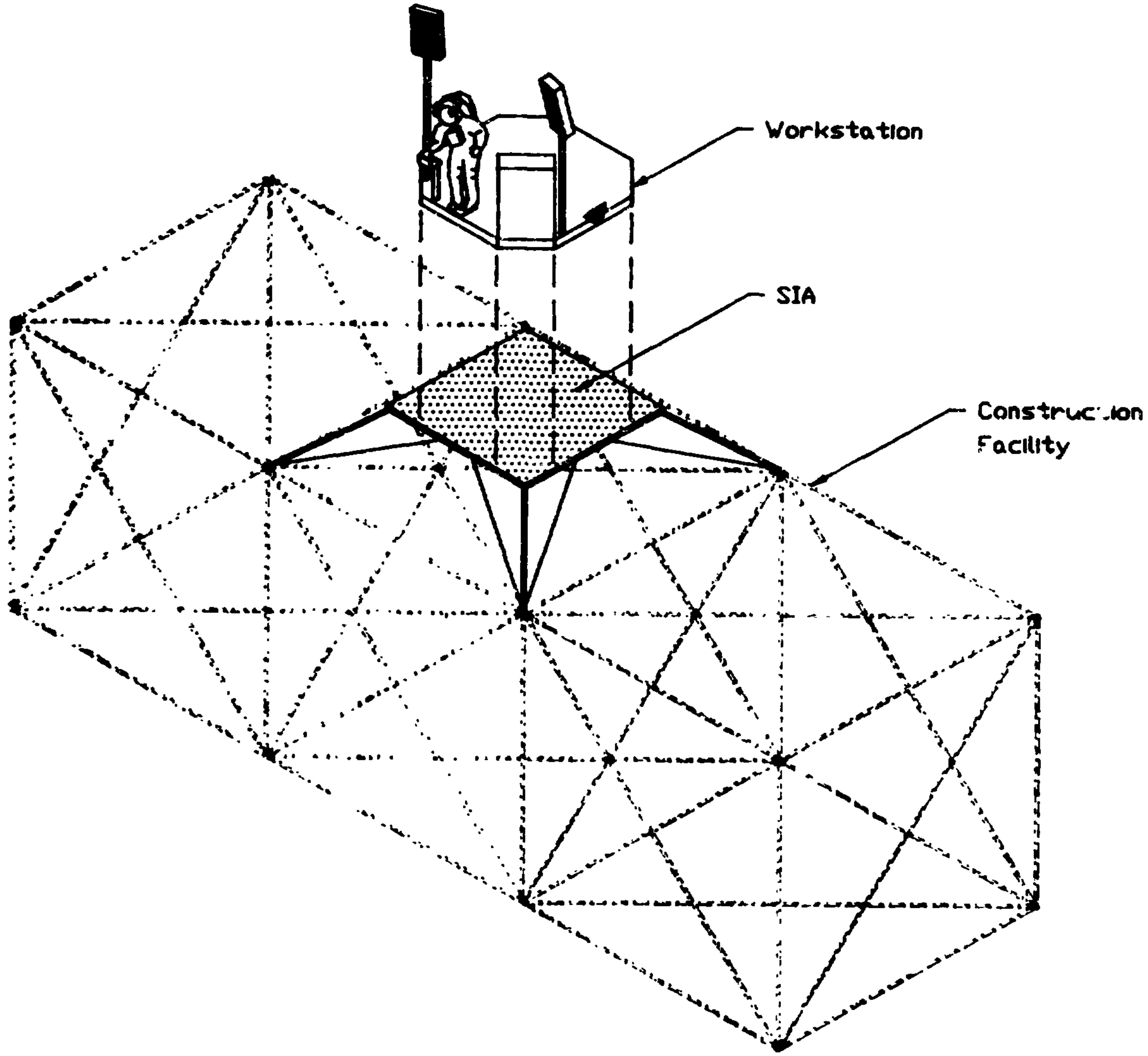
Surrogate Payload Bay



Work Station Concept

It has been demonstrated, both in neutral buoyancy simulations and in space, that EVA tasks can be performed more efficiently when the crew member works from foot restraints. In addition, construction times will be shortened if the parts and equipment needed for construction are close at hand. Therefore, a construction facility must provide a work station that will provide these and other accommodations. Shown in the figure is a concept for a dual purpose work station. While attached to a Structural Interface Adapter (SIA) it can be used as a fixed work station, and by using the Mobile Service Center (MSC), it becomes a portable work station. The SIA provides electrical power for lighting and other electrical needs when the platform is being used as a fixed work station, and for battery recharging when it is being stored. It becomes a portable work station by using the MSC to position it at a remote site. Several grapple fixtures are provided to allow a variety of MSC attachment locations. The work station is large enough to provide lighting, tools, and an area for attachment of containers of components needed for the construction project.

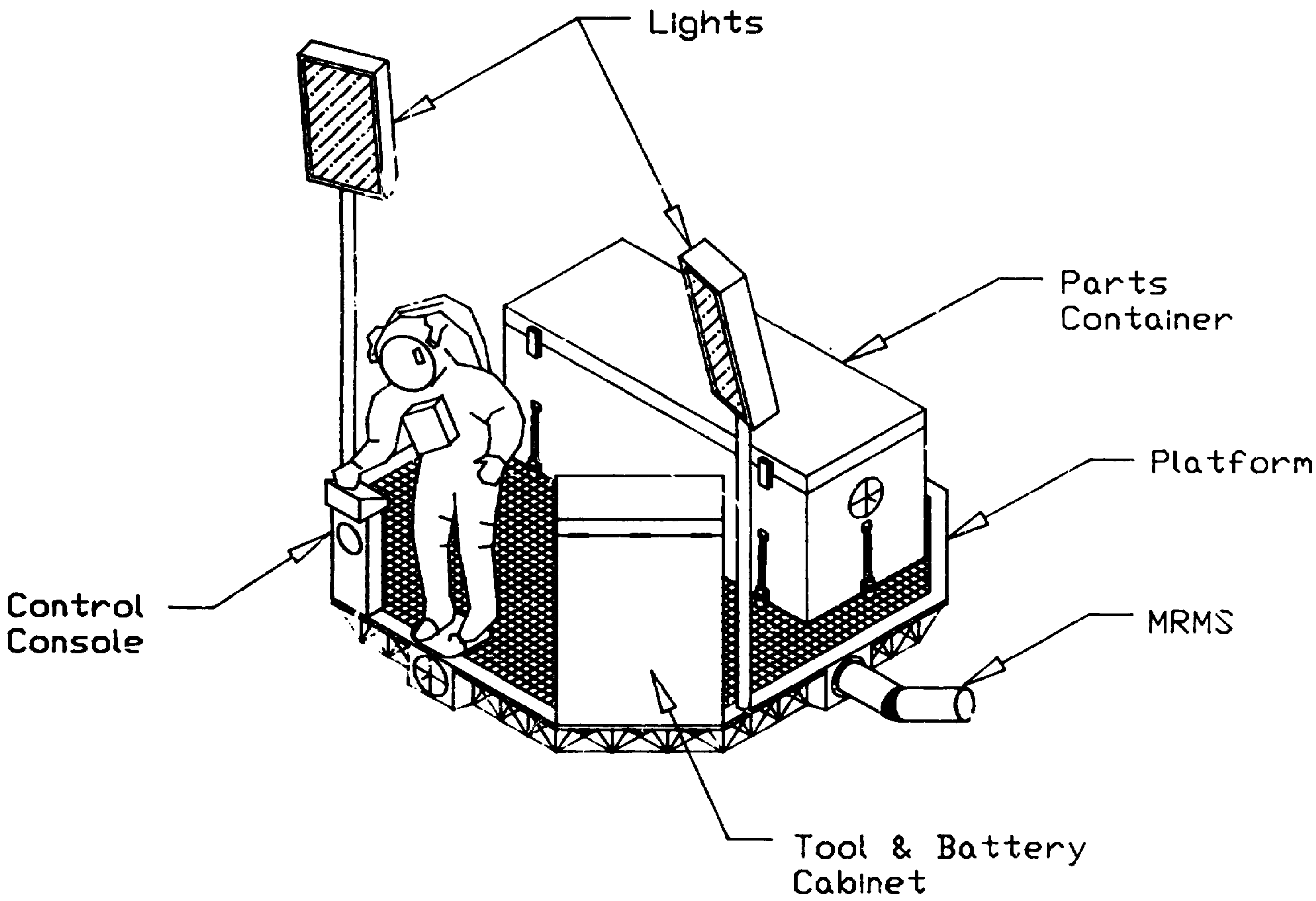
Portable Work Station Concept



Portable Work Station

Shown here in more detail, the work station is made up of a platform whose surface is a grid similar to the generic storage platform previously discussed. It is approximately 4 meters across (capable of being transported to the station within the STS cargo bay diameter) and accommodates a wide variety of attachment locations for foot restraints and tie-downs for equipment and components. Lighting for illumination during dark side passes and shadowed areas is provided by two arrays of lights positioned on either side of the primary foot restraint location. Video coverage is provided by portable video cameras attached to portable and adjustable stands Generic tools and other small equipment are stored in a cabinet within easy reach of the EVA crew. Also contained in that cabinet are rechargeable batteries used to provide electrical power when the work station is attached to the MSC. On the opposite side of the crew member, is a control console used to control such functions as lighting, communications, instrumentation, video coverage, heads-up visual displays, etc. It is also used to provide the crew member with control of the MSC position when used as a portable work station.

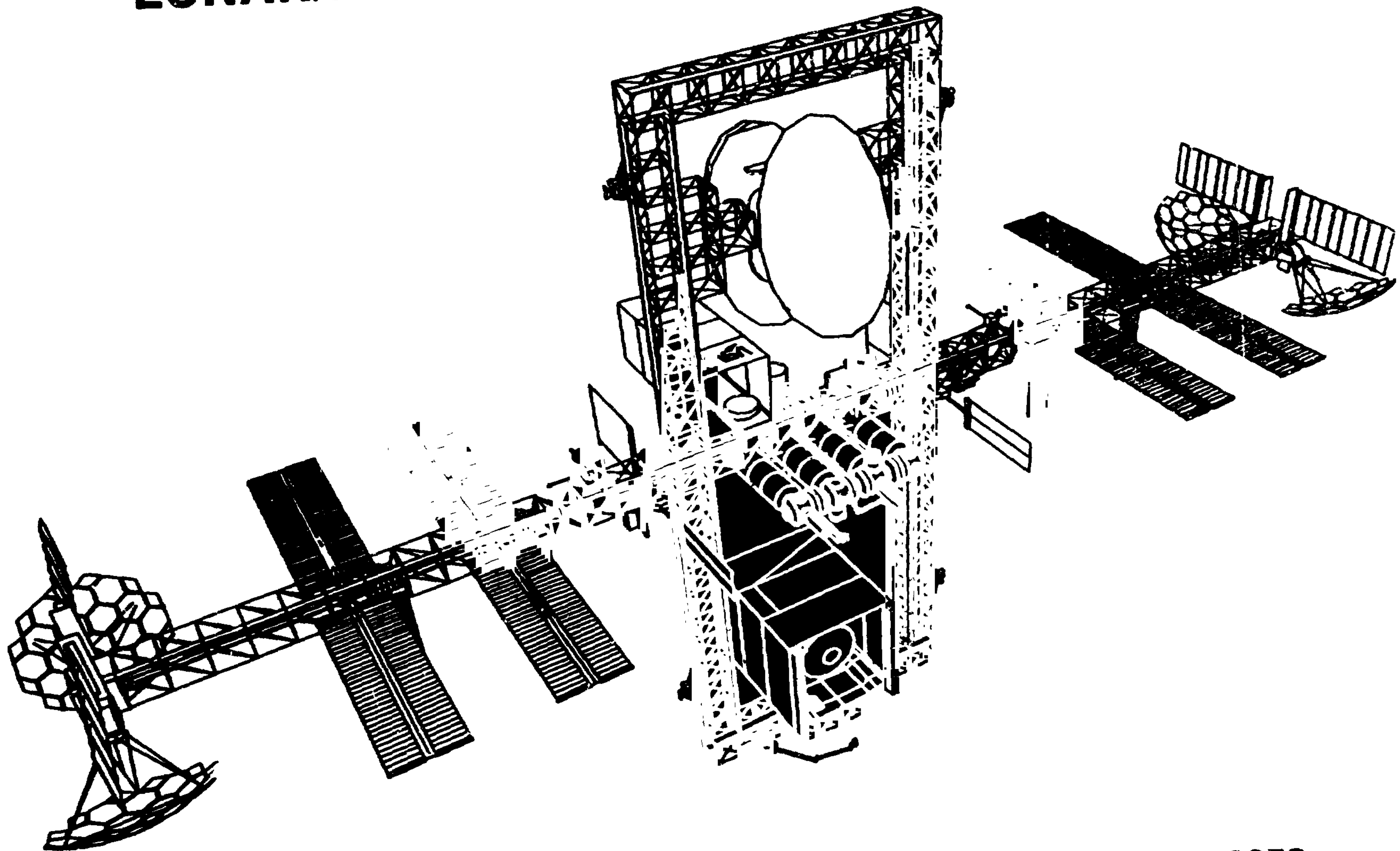
Portable Work Station



Lunar/Mars Transportation Node

Following several stages of evolution, Space Station Freedom is envisioned to become a transportation node supporting lunar and Mars explcration. This drawing shows the facilities to accomplish these missions as well as satellite and OTV servicing. The construction facility described in this paper is the initial evolutionary step in achieving this goal.

LUNAR/MARS TRANSPORTATION NODE



LaRC SSFO

Summary

In summary, a construction facility is needed for technology development demonstrations in support of NASA's Pathfinder Program, for near term construction projects such as Geo Platforms and LDR, and for scientific experiments. The facility proposed here is a cost effective solution because it is a modest size facility that makes use of components that are common to Space Station Freedom. It provides benefits to SSF by providing a portable EVA work station needed for SSF external maintenance and repair. The concept includes both internal and external storage locations for spare parts, components, tools and other assembly aids. It also enhances the location of the microgravity envelope within the modules by lowering the station's center of mass. And, finally, it is the next step in the evolution of Space Station Freedom toward becoming the space transportation node of the future.

Summary

- A construction facility is needed
  - Technology development demonstrations
  - Near term construction projects
  - Science experiments

- The proposed facility is a cost effective solution
  - Modest size
  - Commonality

- Benefits to Space Station Freedom
  - Portable work station
  - Internal and external storage locations
  - Microgravity enhancement
  - Supports Space Station Freedom evolution

WELDING/BRAZING FOR SPACE STATION REPAIR

D. W. Dickinson
Ohio State University

H. W. Babel
McDonnell Douglas Astronautics

H. R. Conaway
Rocketdyne Division

W. H. Hooper
Martin Marietta

Fabrication and Repair Candidates

Throughout the 30 year operation of Space Station Freedom, it is reasonable to assume that structural and operating system damage and deterioration will occur through normal use, operations accidents, and/or collision with debris. It is likely that some of this damage will be of immediate urgency without the availability of identical replacement parts. "In situ" repair will become mandatory.

Three primary bonding assembly methods have been identified as candidate techniques for "In situ" repair of this damage. These techniques include adhesives or adhesive bonding, mechanical fasteners, and welding and brazing techniques. Typical examples of each of these techniques as repair candidates will be presented.

FABRICATION AND REPAIR CANDIDATES

THREE PRIMARY ASSEMBLY METHODS

- 0 ADHESIVES
- 0 MECHANICAL FASTENERS
- 0 WELDING AND BRAZING

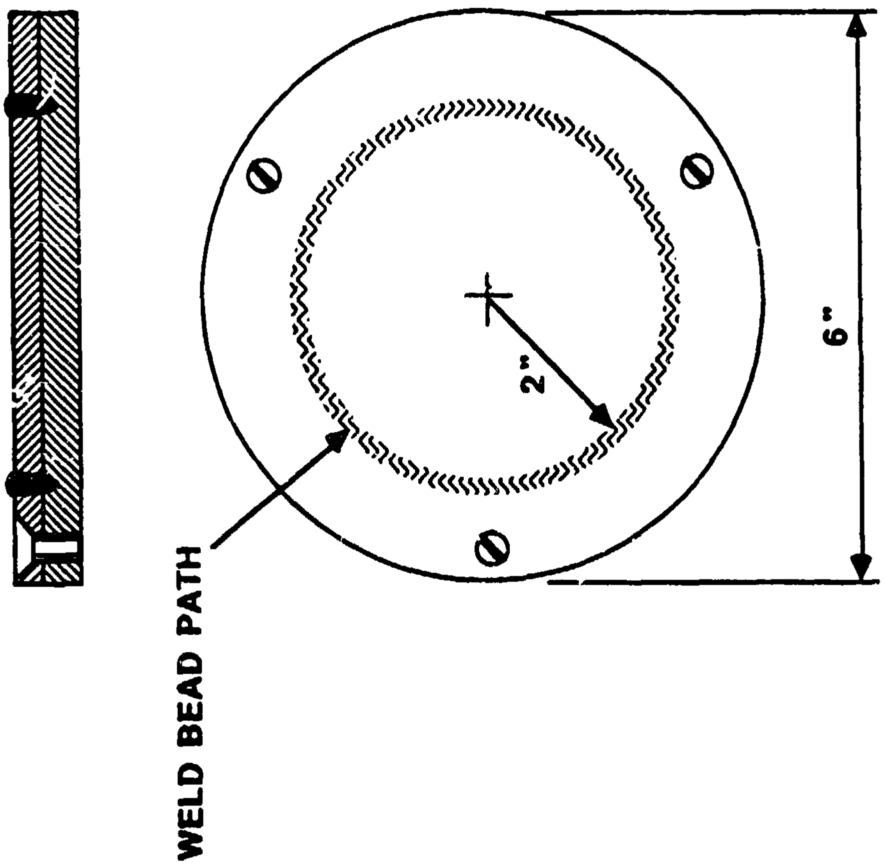
Debris Penetration of Module Panel

A penetration impact to the 1/8 inch 2219 aluminum shell grid panel of a module is simulated in this figure. The use of an "adhesive tape system employed from the inside of the module to effect a repair was investigated by a major aerospace company. This system may provide some immediate relief from the damage but the long term viability is questionable. This is rather like "applying a band aid to a pressure vessel leak."

Ground base welding repair techniques have been developed and have been successfully used in almost every major industry. Welding alternatives need to be developed for space module vessels.

Welded Repair Patch

The Martin Marietta Company has proposed a weld repair patch technique for module repair as illustrated in this figure. The patch, ideally also made from 2219 aluminum, could be affixed over the damaged area and a circular weld bead repair made through the patch and into the module wall to seal off the damaged area. The welded patch would provide a reliable, long term, leak tight repair which could be made from either the outside or inside of the vessel with equal reliability. The welding process under development by Martin Marietta to bond this patch will be described in more detail below.

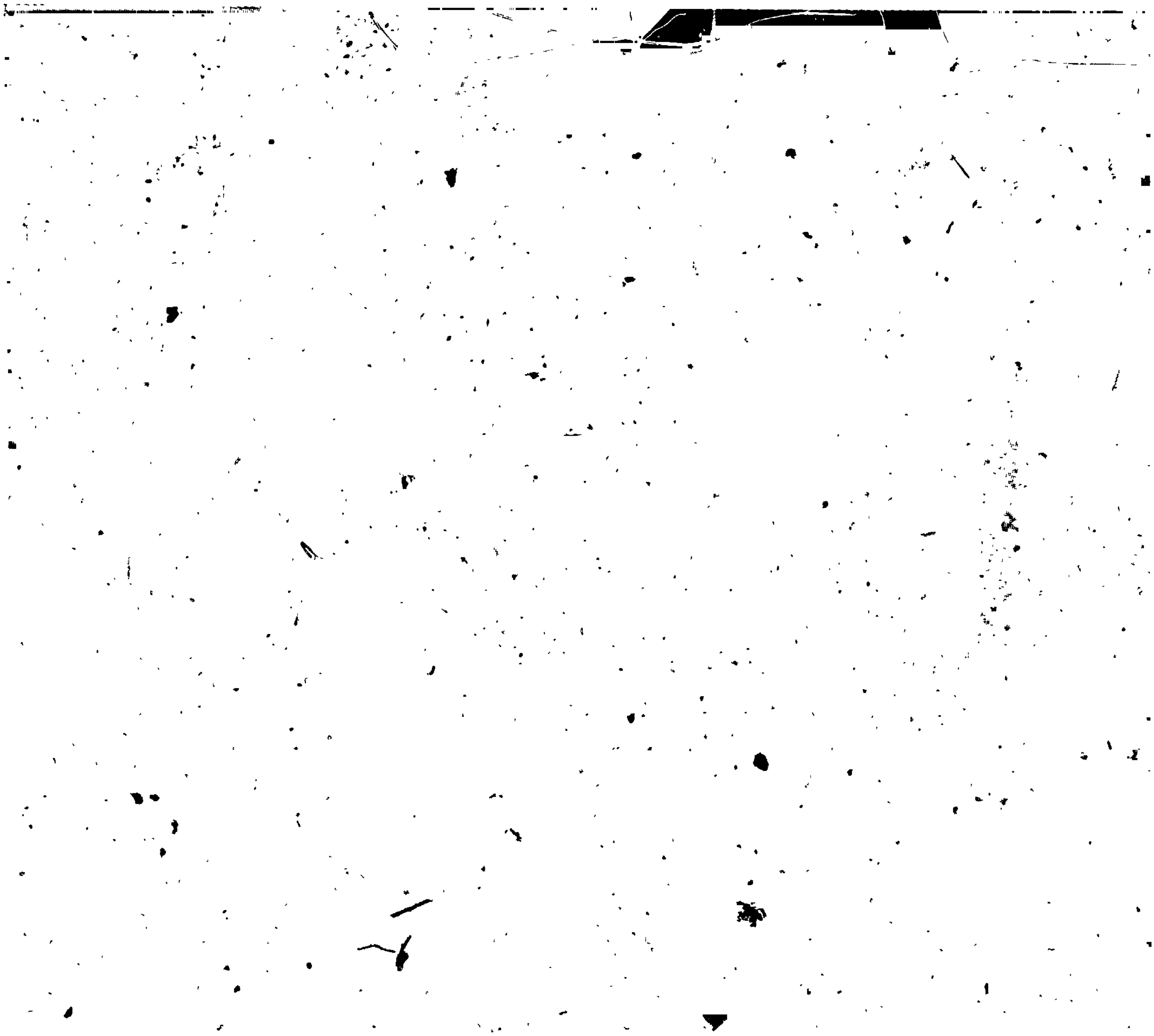


Panel #1 2219 ALLOY

Mechanical Assembly of Utility Fluid Line

A second example where repair may be required might be on a broken fluid line. The current repair procedure might consist of cutting the damaged fluid line and installing a "quick disconnect" mechanical coupling.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



Space Station Utility Systems

The 1989 proposed operating fluids and operating pressures for thermal, propulsion and other fluid lines are presented in this figure. The relatively high operating pressures should be noted. The long life reliability of many mechanical disconnects at these operating pressures is uncertain.

However, welded tube and pipe assemblies operating at these pressures are routinely used on earth base construction in chemical producing plants, nuclear reactors, refrigeration and other critical facilities.

SPACE STATION UTILITY SYSTEMS

SYSTEM	OPERATING FLUID	PRESSURE (psi)
Thermal	Ammonia	65 and 130
Propulsion	Hydrogen/Oxygen	500 to 3000
Fluids	Nitrogen	600 to 6000
	Waste Gases	30 to 1000
	Water	10 to 60

Welding Has The Most Potential

In earth base construction, welding and brazing has traditionally proven to be a reliable and cost effective means of fabrication and repair. With appropriate development, it could prove to be an enabling technology for in-space repair and construction, as well.

OF THE FABRICATION AND REPAIR CANDIDATES -

WELDING HAS THE

MOST POTENTIAL

NASA has had some successful in-space welding/brazing trials, primarily on space lab. These trials, however, have been of limited extent and have not caused a modification of the opinion in NASA Standard-3000. That opinion remains: "Soldering, welding, brazing, and similar operations during maintenance shall be minimized."

NASA-STD-3000/VOL IV

PARAGRAPH 12.3.1.1

Item t.

Soldering, Welding, and Brazing -

Soldering, welding, brazing, and similar operations during maintenance shall be minimized.

Soviet Aerospace Fabrication - An Overview (In-Space Welding)

On the other hand, the Soviets have made an "all out" commitment to in-space welding. Beginning as early as 1964, they have investigated a large number of different fusion welding processes and, despite some narrowly avoided disasters, they have intensified their efforts in welding in space developments.

Soviet Aerospace Fabrication — An Overview

In–Space Welding

- Soviet welding–in–space project dates to 1964 when an overall evaluation program was adopted
- Fusion welding processes evaluated included GMA, GTA, plasma arc and electron beam
- First actual welding in space occurred in October, 1969 with the E.B., plasma and GMA processes
    - During this first E.B. experiment, a rotating table malfunctioned and the electron beam burned thru the container into the space ship wall
        - Did not penetrate because in Mr. Paton's opinion, earth's magnetic field caused beam to curve
    - Despite this narrowly avoided disaster, Soviets standardized on E.B. as the one process to use

C3

Soviet Aerospace Fabrication - An Overview (Background)

In order to obtain first hand knowledge of the Soviet In-Space welding efforts, the American Welding Society arranged for a visit to Soviet aerospace facilities by delegates from several U.S. aerospace companies. The Paton Electric Welding Institute in Kiev served as the host institution, and Mr. Boris Paton, Director of the Institute, served as the official host. Mr. Paton is a high ranking member of the Soviet Academy of Sciences and has been charged with coordinating advanced materials development for the Soviet space effort, thus he provided an effective link to Soviet technology.

Soviet Aerospace Fabrication — An Overview

Background

- Soviets invited a delegation of U.S. aerospace representatives to visit Soviet Union to learn first–hand Soviet fabrication techniques for their space program
  - The invitation, extended from the Paton Welding Institute, came through the American Welding Society (AWS)
  - The delegation consisted of:
    - Dr. Dave Dickinson, Chairman, Dept. of Welding Engineering, Ohio State University
    - Dr. Hank Babel, McDonnell Douglas, Huntington Beach
    - Mr. Bill Hooper, Martin Marietta, Michoud Division
    - Mr. Jim Walker, Past President, AWS
    - Mr. Hal Conaway, Rocketdyne

Rockwell International
Rocketdyne Division

Soviet Aerospace Fabrication - An Overview

The American Aerospace Delegation spent two weeks in July 1989 visiting five prominent Soviet Aerospace related facilities in Kiev and near Moscow. In many instances, this was the first Western Delegation to visit previously restricted areas. Discussions on materials, structures, instrumentation, training, and fabrication techniques for ground base and in-space operations were held.

Soviet Aerospace Fabrication — An Overview

- The U.S. delegation spent two weeks (2–14 July 1989) in the Soviet Union visiting:
  - The Paton Welding Institute, Kiev
  - The Cosmonaut Training Center, Star City
  - NPO "Komposit," Moscow area
  - NPO "Energija," Moscow area
  - NIITM Research Institute of Mechanical Engineering, Moscow area

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Process Under Consideration - Electron Beam Welding ...

From the discussions held in the Soviet facilities, and from developmental activities within the American Aerospace Companies (and other companies throughout the world), it is obvious that a great number of welding and bonding processes are under consideration for in-space construction and repair. The list presented in this figure is by far not exhaustive.

Process experience in some of these areas will be highlighted below, starting with several examples of electron beam welding, some of which have been space demonstrated while others are under development.

PROCESSES UNDER CONSIDERATION

0 Electron Beam Welding/Cutting/Brazing

0 Arc Welding

0 Laser Welding

0 Explosive Bonding

0 Induction Welding/Brazing

0 Microwave Bonding

0 Thermit Welding

EVA Electron Beam Welding System

A significant portion of the Soviet in-space welding equipment development effort has been directed at producing and demonstrating the viability of the EVA Electron Beam Welding System illustrated in this figure. This system is called the "Universal Versatile Hand Tool". This 1 KW electron beam devices has been designed for manual cosmonaut use with welding, brazing, cutting and vapor deposition of coating capability. The varying processes are obtained by focusing or de-focusing the beam and by directing the beam on a crucible containing coating materials.

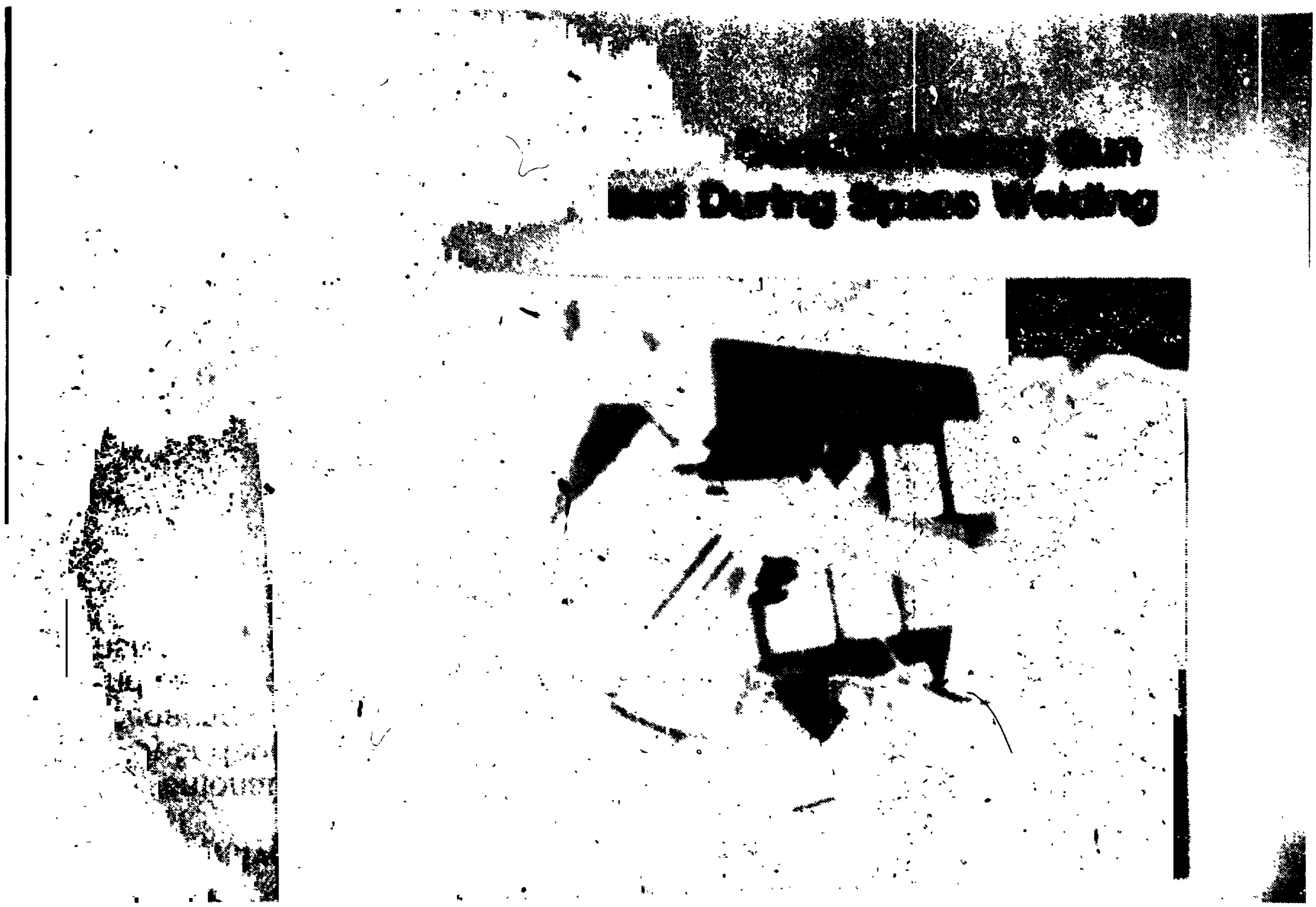
The 2.2 kilogram gun obtains its 1 KW of power from the spacecraft (the primary is 27 volts DC with and invertor). The gun voltage is only 18,000 volts, maximum, and the maximum beam current is 70 MA.

Lt. Gen. Djanibekov Demonstrating Gun

In this figure, Cosmonaut Vladimer Djanibekov is demonstrating the use of the "Universal Versatile Hand Tool" for welding. The samples to be welded are mounted in a "flip up" tray in the rear of the power supply unit. Manual welds are made with the gun assembly.

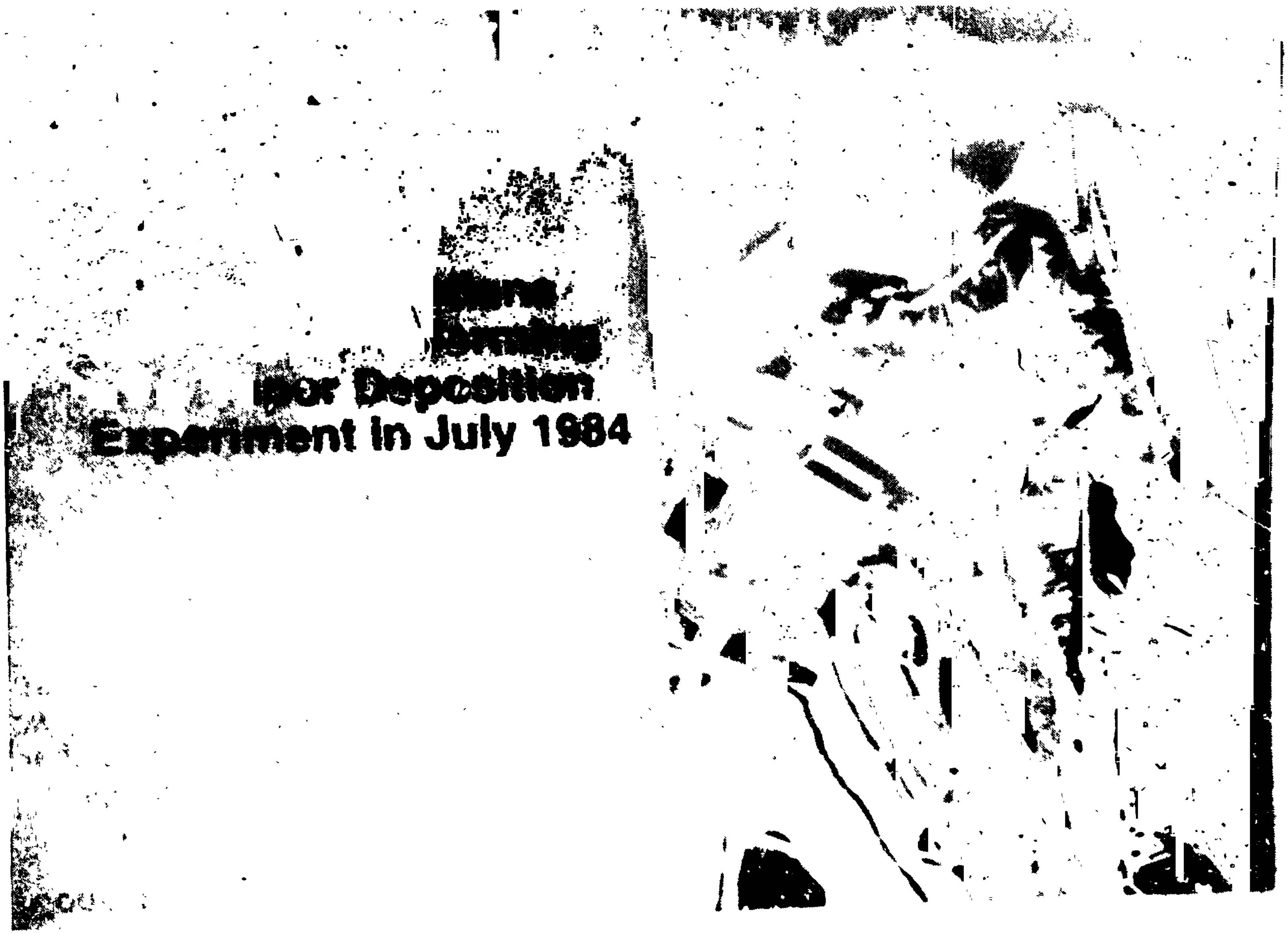
In space experiment were performed by Cosmonaut Djanibekov which demonstrated the feasibility of cutting and welding steel, aluminum, and titanium alloys up to 3 mm (0.120 inch) thick in the butt weld configuration. This should be sufficient for most of the current U.S. material design thicknesses.

The Soviets are currently working on a unit which will provide 2 KW of power and have wire feeding capability for welding thicker materials in a weld overlap or prepared groove configuration. This will open considerably wider space construction options.


Gun
During Space Welding

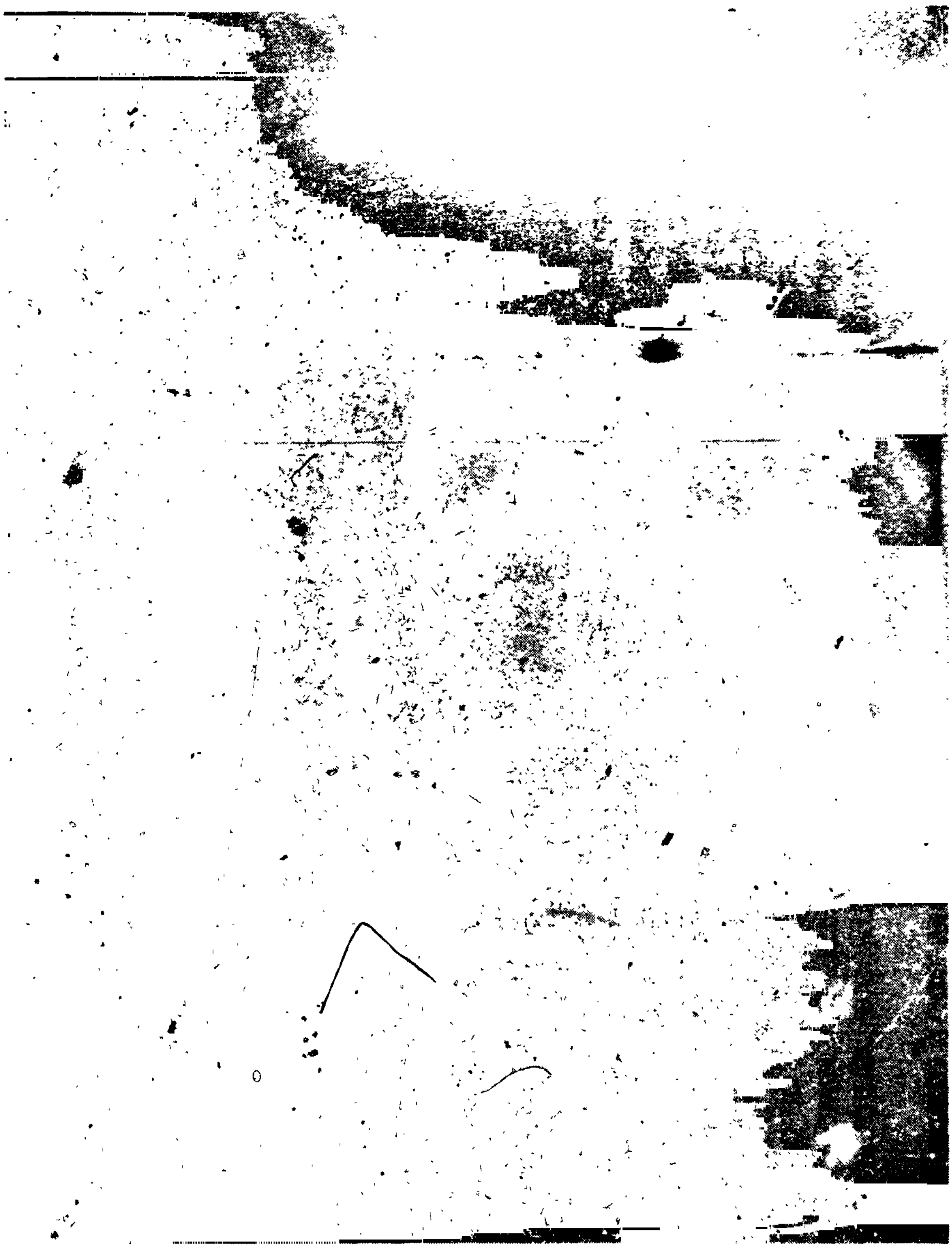
Cosmonaut Svetlana Savitskaya Performing EVA Vapor Deposition

Cosmonaut Savitskaya performed an EVA experiment in July 1984 to put a vapor deposition coating on a sample mounted on the "flip up" holder. Vapor coatings of gold, silver, and copper have been demonstrated in space. Ground base experience with electron beam vapor deposition is much more extensive.


Deposition
Experiment in July 1984

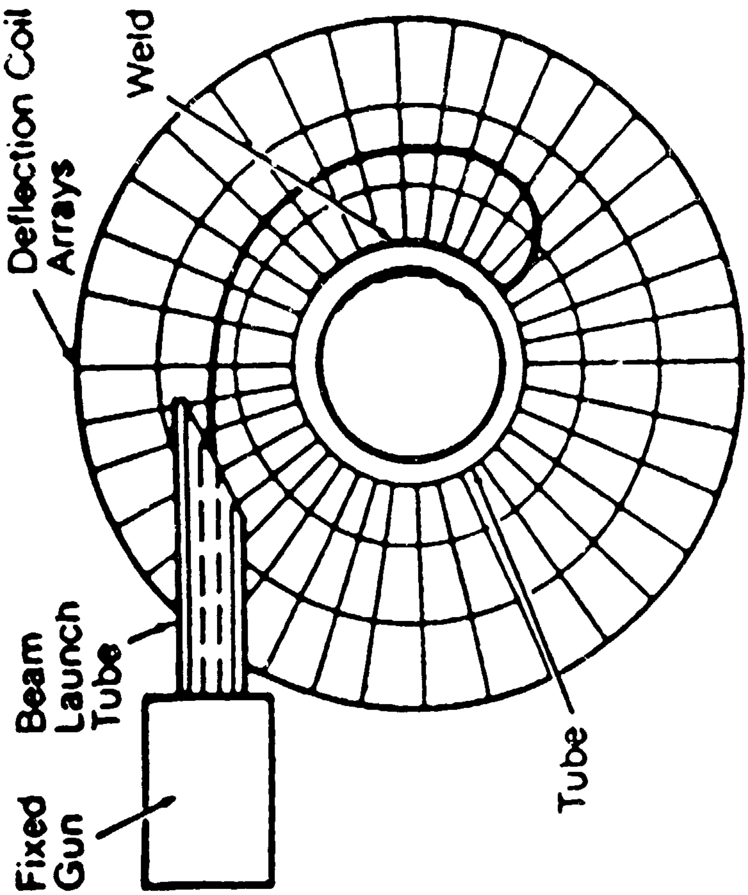
Concept of EB Welding Trusses

In addition the Soviets have developed several concepts for the original construction and repair of space trusses. Here is shown a concept for joining legs of metallic tubular trusses. Development of a deployable triangular truss with electron beam welded or brazed nodes has been performed and ground tested.



Electron Beam Tube Weld

In another electron beam development efforts, a European firm, Babcock Power Ltd., is developing an electron beam welding device for in-space welding of tubes as illustrated in this schematic. The electron beam is controlled and deflated through 360 degrees around the tube by an array of deflection coils. Unwrapping the beam will produce a butt weld around the circumference joining the two tubes. Note that this system is ideally designed for automated welding which could reduce some EVA time. In addition, the beam is completely enclosed thus reducing any risk of generated x-rays during electron beam welding.

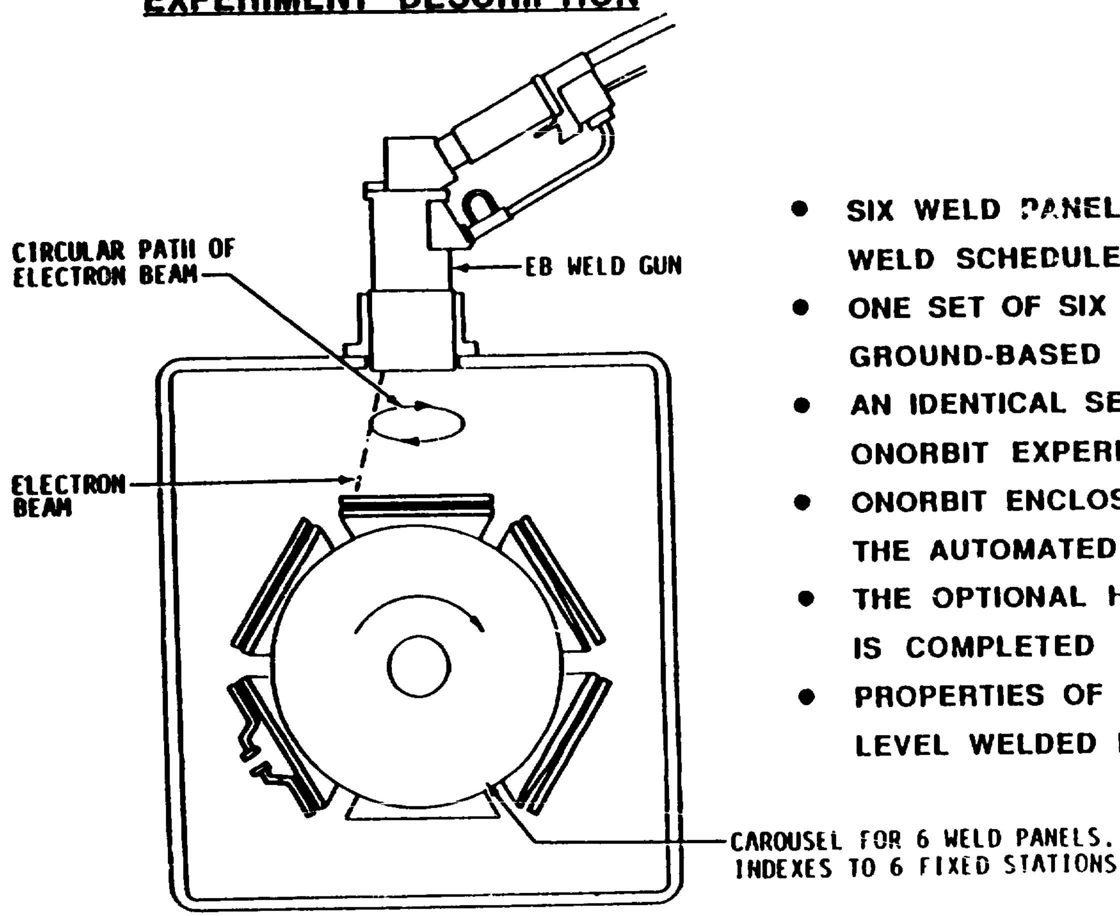

Deflection Coil
Arrays
Weld
Beam
Launch
Tube
Fixed
Gun
Tube

On Orbit Electron Beam Welding Experiment

As part of an Outreach Experiment, Martin Marietta has performed an experimental definition to develop an on orbit electron beam welding gun which can be used as an automated system or as a hand held unit. The gun power will meet or exceed those of the Soviets and contain safety features not found in the Soviet unit. The experimental demonstration calls for the evaluation of multiple welded panels to evaluate varying welding parameters and panel configurations.

ONORBIT ELECTRON BEAM WELDING EXPERIMENT

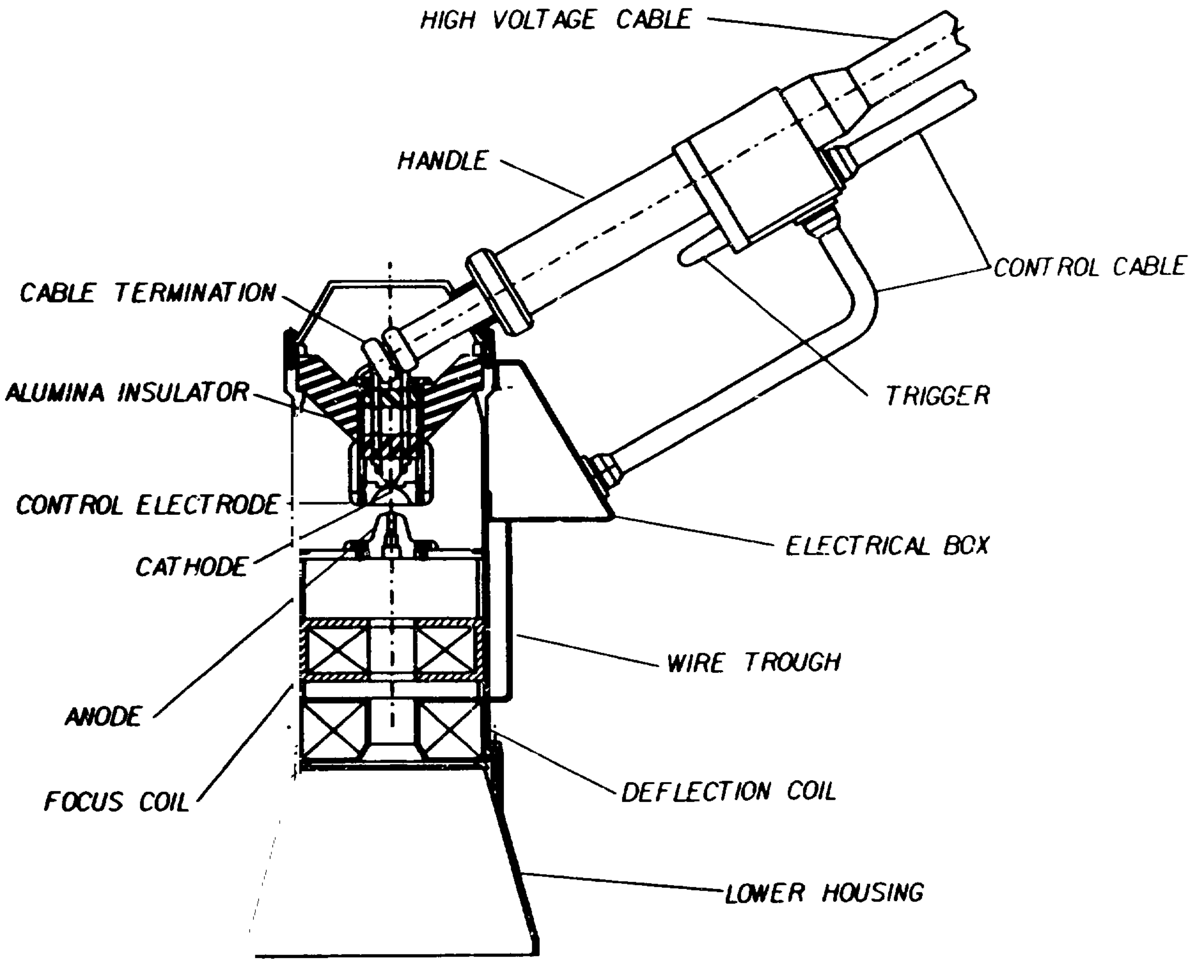
EXPERIMENT DESCRIPTION



- SIX WELD PANEL CONFIGURATIONS AND WELD SCHEDULES ARE DEVELOPED
- ONE SET OF SIX PANELS IS WELDED IN GROUND-BASED EXPERIMENT
- AN IDENTICAL SET IS MOUNTED FOR ONORBIT EXPERIMENT
- ONORBIT ENCLOSURE IS PORTED TO SPACE: THE AUTOMATED CYCLE OF WELDS IS REPEATED
- THE OPTIONAL HAND-HELD WELDING EXPERIMENT IS COMPLETED
- PROPERTIES OF ONORBIT WELDED AND GROUND-LEVEL WELDED PANELS ARE COMPARED

On Orbit EB Gun

This frame is a cut away schematic of the Martin Marietta On Orbit electron beam gun showing internal components. The deflection coils are used to automatically rotate the beam in order to make the repair weld as illustrated earlier for the space station module panel weld repair. Note that the lower housing on the gun completely encloses the welding beam thus providing safety.



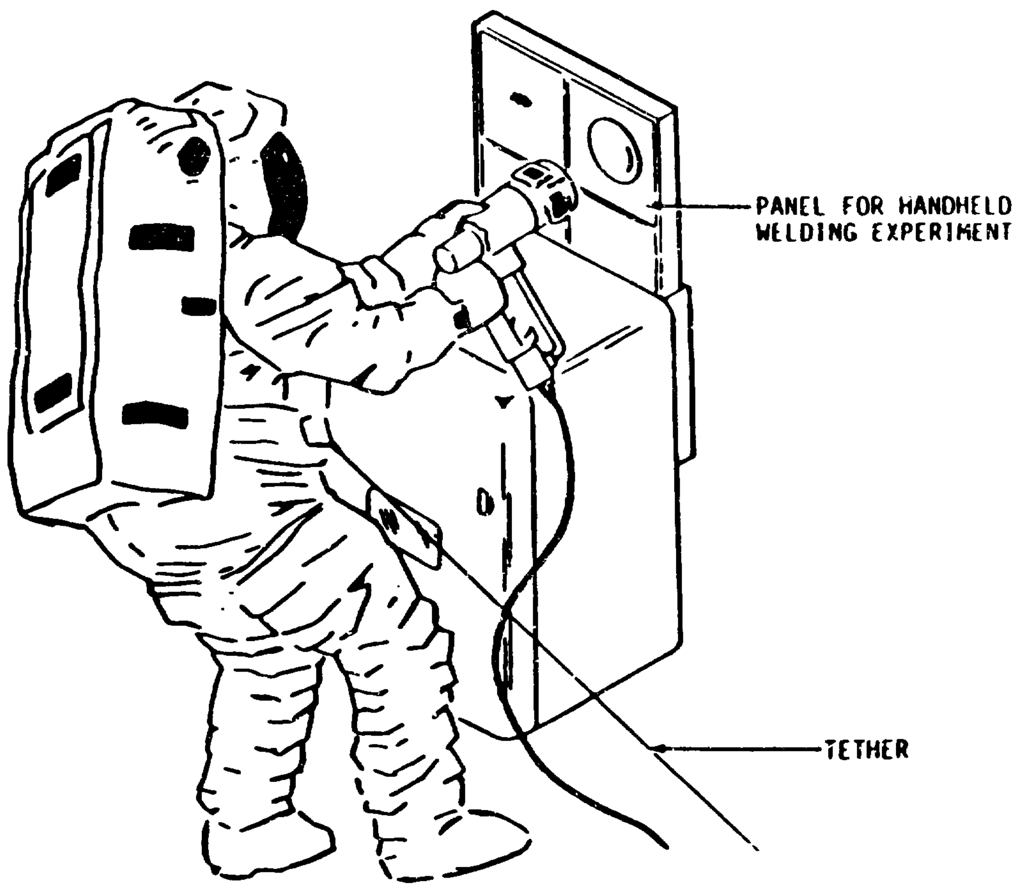
On Orbit EB Gun

MARTIN MARIETTA PROPRIETARY

MARTIN MARIETTA MANNED SPACE SYSTEMS

On Orbit Electron Beam-EVA

This figure illustrates the use of the Martin Marietta electron beam gun in a hand held welding configuration.


PANEL FOR HANDHELD
WELDING EXPERIMENT
TETHER

Processes Under Consideration- Arc Welding

The Soviet Union has performed extensive research on conventional arc welding processes including gas metal arc, gas tungsten arc, and plasma arc welding before deciding to concentrate the majority of their effort on electron beam welding. In each case they demonstrated the viability of arc welding in space, but felt that better control was available through the electron beam route. A recent process modification of gas tungsten arc welding by Rocketdyne has demonstrated remarkable promise in ground base testing which could lead to advantages unforseen by the Soviets.

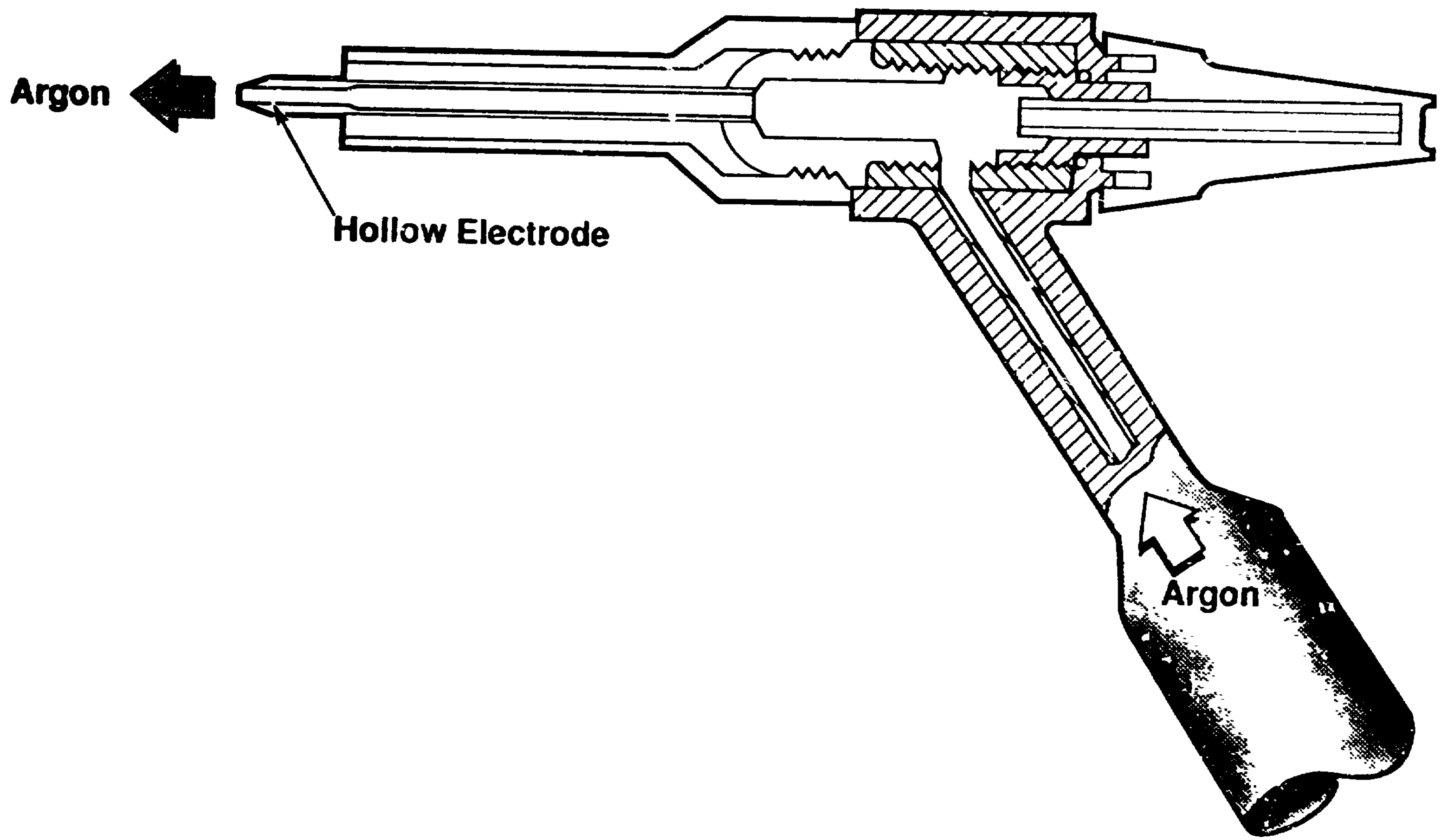
PROCESSES UNDER CONSIDERATION

- 0 Electron Beam Welding/Cutting/Brazing
- 0 **Arc Welding**
- 0 Laser Welding
- 0 Explosive Bonding
- 0 Induction Welding/Brazing
- 0 Microwave Bonding
- 0 Thermit Welding

Rocketdyne Vacuum GTAW Torch

A schematic of this modified gas tungsten arc welding torch developed by Rocketdyne is presented in this figure. In this modification, the normal solid tungsten electrode is replaced by a hollow tungsten electrode. The argon gas used for the arc plasma is fed through this electrode in conventional gas tungsten arc welding. This arrangement provides positive arc stabilization in vacuum environments. No shielding gas is required.

Rocketdyne Vacuum GTAW Torch



Vacuum Gas Tungsten Arc System

Using the modified system with a 0.020 inch hole through the electrode and an extremely small gas flow rate of only 1 cubic foot per hour for arc maintenance, excellent arc welds produced in vacuum have been demonstrated. Arc starting and control were excellent. And the vacuum was observed to purify the weld and generally produce a better weld than available in conventional arc welding.

Vacuum Gas Tungsten Arc System

- Rocketdyne developed hollow electrode concept
  - Small (0.020 in.) hole through an 0.093 in. dia tungsten electrode
  - Gas flow less than 1 cfh
  - Welds are "deep/sound"
  - Welds larger than conventional GTAW welds with same energy
- Advantages of hollow tungsten concept for space based welding
  - No differential pressures
  - Excellent arc starting capabilities
  - Vacuum purifies the weld
  - Vacuum helps clean parts

Rockwell International
Rocketdyne Division

Processes Under Consideration - Laser Welding

The laser welding process on earth is becoming a maturely developed technology offering advantages of speed and control. However, only a small amount of space laser welding research is underway.

PROCESSES UNDER CONSIDERATION

0 Electron Beam Welding/Cutting/Brazing

0 Arc Welding

0 **Laser Welding**

0 Explosive Bonding

0 Induction Welding/Brazing

0 Microwave Bonding

0 Thermit Welding

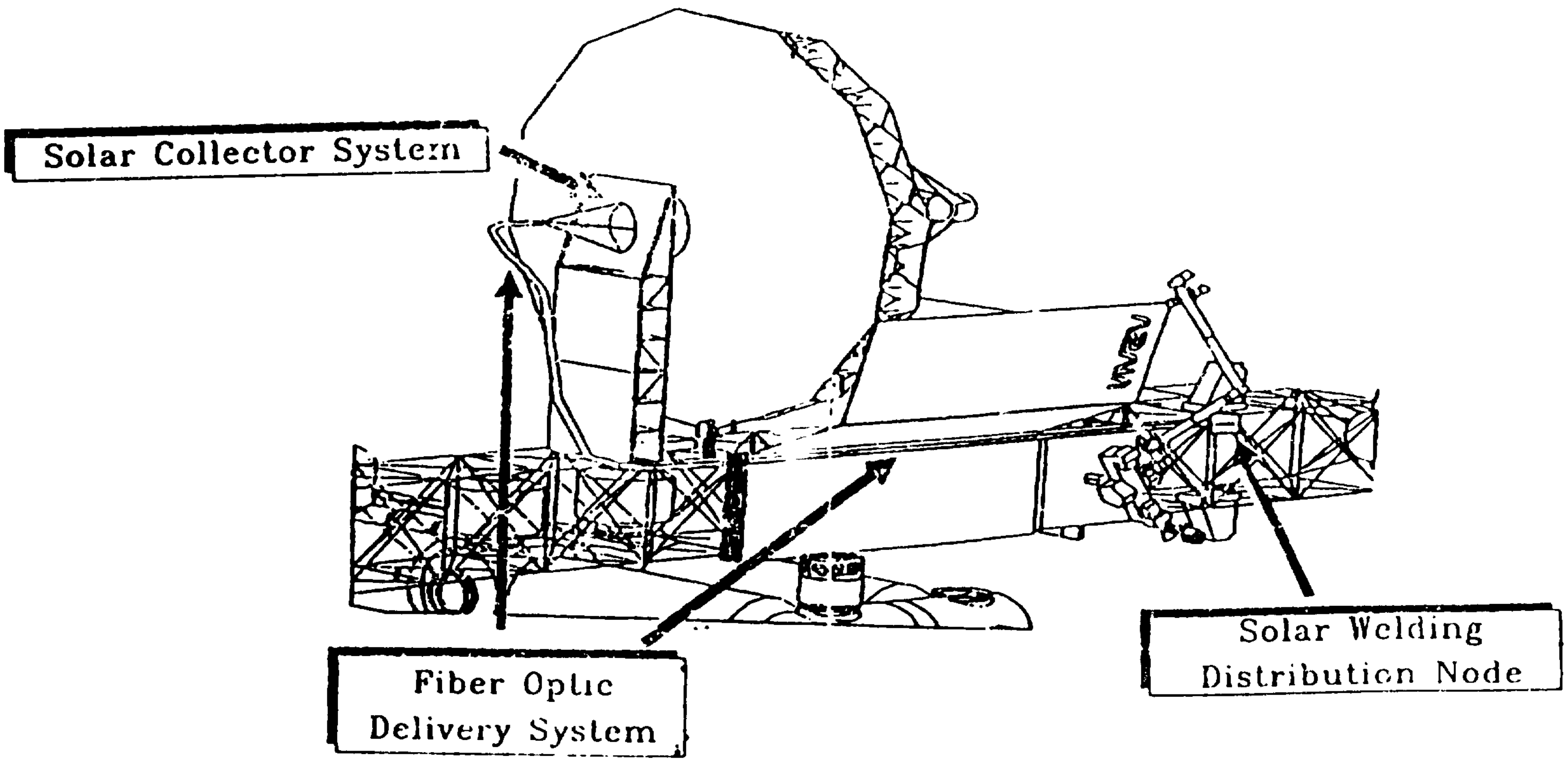
Current Solar Collector Experiments

The University of Alabama in Huntsville is proposing the use of solar Collectors, similar to those proposed for solar dynamics furnaces, for supplying the energy for pumping in-space lasers. It is proposed that the laser beam would be distributed through a fiber optics system to a hand held welding gun or an end effector on a robotic weld repair unit. Laser welding devices such as these can provide all the advantages and options available on the Soviet electron beam system without as great a concern about secondary x-ray generation.

LASER WELDING IN SPACE

UAH

CURRENT SOLAR COLLECTOR EXPERIMENTS CAN ASSIST IN DEVELOPING SOLAR PUMPED LASER TECHNOLOGY



Current concepts being developed for the Solar Dynamics Furnace and the Large Deployable Reflector Assembly will also provide a testbed for applying solar pumped lasers to repair and/or assembly operations.

CO Lasers for Space Applications

In an independent effort, a program definition to develop a Carbon Monoxide laser is underway. This unit would provide high power at high efficiency while maintaining lighter weight and more compact design than other types of lasers.

CO LASERS FOR SPACE APPLICATIONS

* **CO AS HIGH AS 45% EFFICIENCY**
  CO_2 10 - 20% EFFICIENCY
  ND:YAG 1 - 5% EFFICIENCY
* **CAN HAVE VERY COMPACT DESIGN**
* **CAPABLE OF VERY HIGH POWER**
  (MITSUBISHI - 10 kW)
* **5 um WAVELENGTH GOOD FOR WELDING AND CUTTING**
* **BEING DEVELOPED IN GERMANY, JAPAN, AND USSR,**
  (PROPOSED PROJECT AT OSU   ONLY U.S. PROGRAM)

OSU

Processes Under Consideration - Explosive Bonding

The use of ribbon explosives or small detonation charges appropriately located on or near parts to be joined can produce a running shock wave at the bond joint. This wave provides both interruption of the interface oxide layer and intimate surface contact under pressure sufficient to produce an inter-atomic bond (cold weld) across the interface.

PROCESSES UNDER CONSIDERATION

0 Electron Beam Welding/Cutting/Brazing

0 Arc Welding

0 Laser Welding

0 **Explosive Bonding**

0 Induction Welding/Brazing

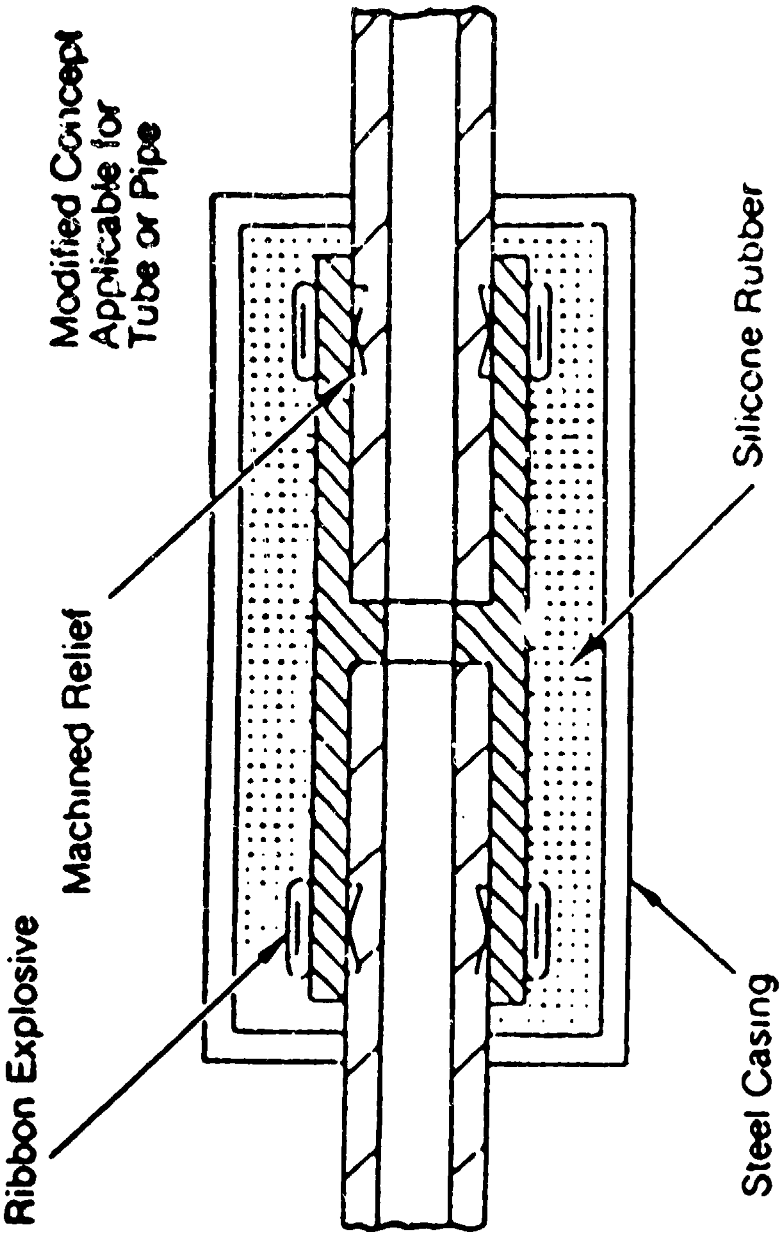
0 Microwave Bonding

0 Thermit Welding

Explosive Welding Setup Appropriate for Tubing

This figure shows a McDonnell Douglas modification of an explosive bonding process developed at NASA-Langley for bonding of tube sections. The tubing to be bonded is inserted into a sleeve around which the explosive ribbon is wrapped. Welds are made rapidly on each side of the tube within a fully enclosed container to avoid and contamination of the space atmosphere. The advantages for emergency repair of damaged truss structural tubing, rather than waiting for replacement parts, is obvious.

A similar explosive bonding system is under development by the Soviets for attaching all the tubes at a nodal point in one operation.


Modified Concept
Applicable for
Tube or Pipe
Machined Relief
Ribbon Explosive
Silicone Rubber
Steel Casing

Processes Under Consideration

In addition to the processes described above, a whole series of other welding and bonding processes are in various stages of development. These include induction welding and brazing for metallic and doped polymer and polymeric composite materials. Microwave bonding for ceramic materials. Transient liquid phase diffusion bonding for metal matrix composite materials. And thermit welding for hard to bond metals and large cross section materials.

PROCESSES UNDER CONSIDERATION

0 Electron Beam Welding/Cutting/Brazing

0 Arc Welding

0 Laser Welding

0 Explosive Bonding

0 **Induction Welding/Brazing**

0 Microwave Bonding

0 Thermit Welding

Boris Paton Statement

In the decades following the first world war, applications where welded construction proved to be more reliable, more cost effective and better than conventional construction and repair techniques were continually identified. To meet the demand for welded construction, a whole series of welding processes were developed during this period.

Now that we are entering a new age of space exploration and development, a fabrication and repair challenge again is occurring. The need for welding applications in repair and original fabrication is appearing. This demand must be met by appropriate process development for the space environment.

As Mr. Boris Paton, Director of the Paton Institute in the USSR says, "In the not too distant future, welding in space will become not an experiment but general practice - as is welding for earthly construction.

"In The Not Too Distant Future, Welding In Space Will Become Not An Experiment But General Practice - As Is Welding For Earthly Construction"

B. Paton
USSR, 1970

Conclusions

The challenge is up to us. The need for welding and brazing for space station repair and construction during station evolutionary phases is clear. Process developments to meet these needs are underway. The time is right to consider welding and brazing for improved fabrication and repair reliability.

CONCLUSIONS

WELDING/BRAZING SHOULD BE CONSIDERED FOR IMPROVED FABRICATION REPAIR RELIABILITY

N93-27841

*PROBE**

A PROPOSED FLIGHT EXPERIMENT TO STUDY EVA ASSEMBLY OF PRECISION SEGMENTED REFLECTORS

Walter (Doug) Heard

NASA Langley Research Center

Hampton, VA

Technology for Space Station Evolution -- A Workshop

January 16--19, 1990

Dallas, Texas

*Precision Reflector Orbital Build Experiment

NASA Langley Research Center   Heard 1-8-90

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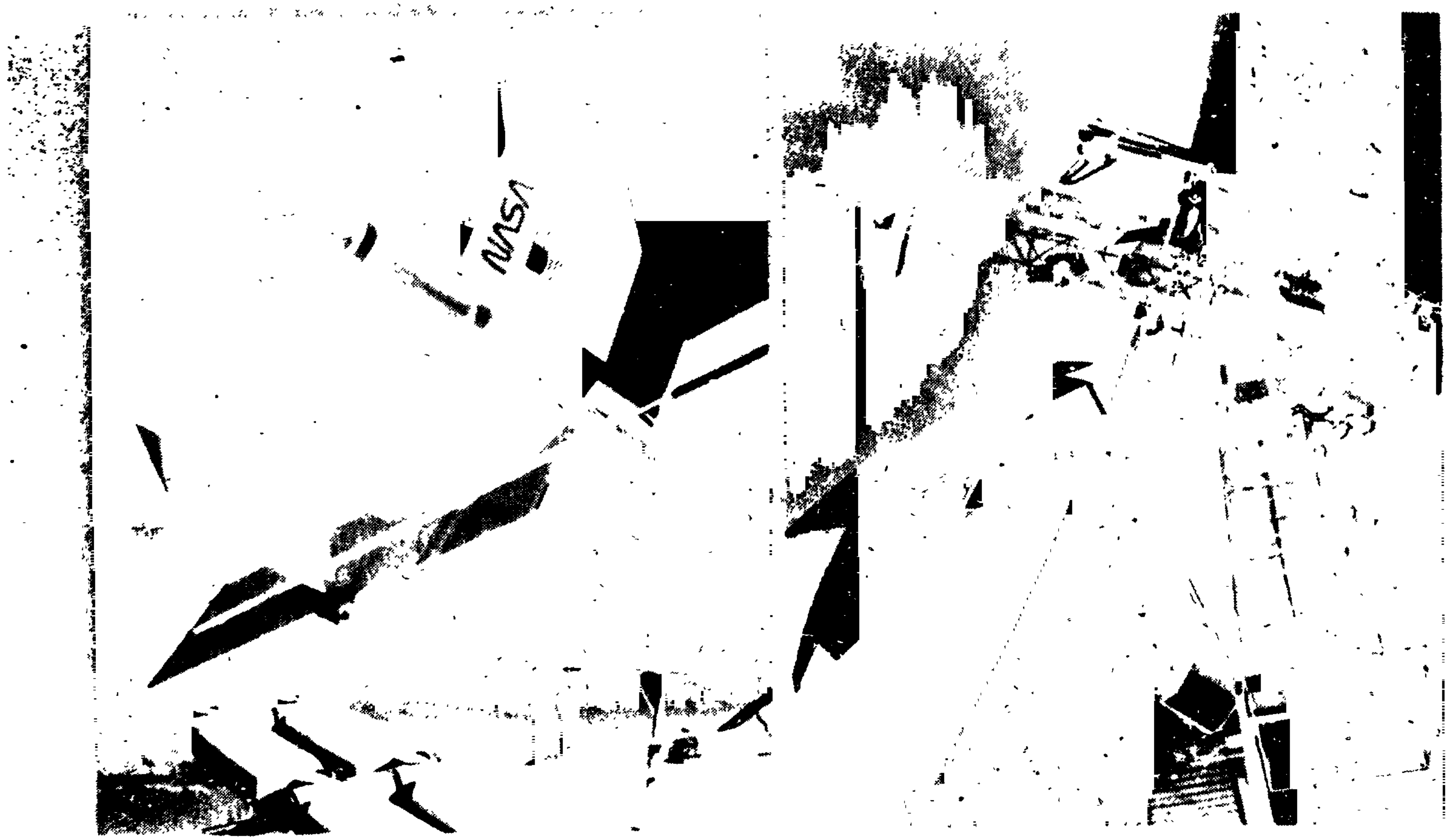
PROBE is a Shuttle flight demonstration experiment designed to study EVA assembly of precision segmented reflectors. The experiment proposal was submitted by the NASA Langley Research Center to the Office of Space Flight in February 1989. Langley was notified on November 3rd that the experiment was recommended by the review board and that funding was being sought for its implementation.

PROBE will support missions being considered for NASA's Global Change Technology Initiative as well as other missions in astrophysics and spacecraft optical communications requiring large precision reflectors. Such reflectors are envisioned to consist of a low-mass backup truss to which the optical surface is attached. Because of their large size, these reflectors will be constructed on-orbit from smaller pieces which can be packaged in the launch vehicle. The technology to be developed with ***PROBE*** also has application for construction of solar dynamic collectors which are planned for the enhanced configuration of Space Station Freedom.

PRECISION SEGMENTED REFLECTORS

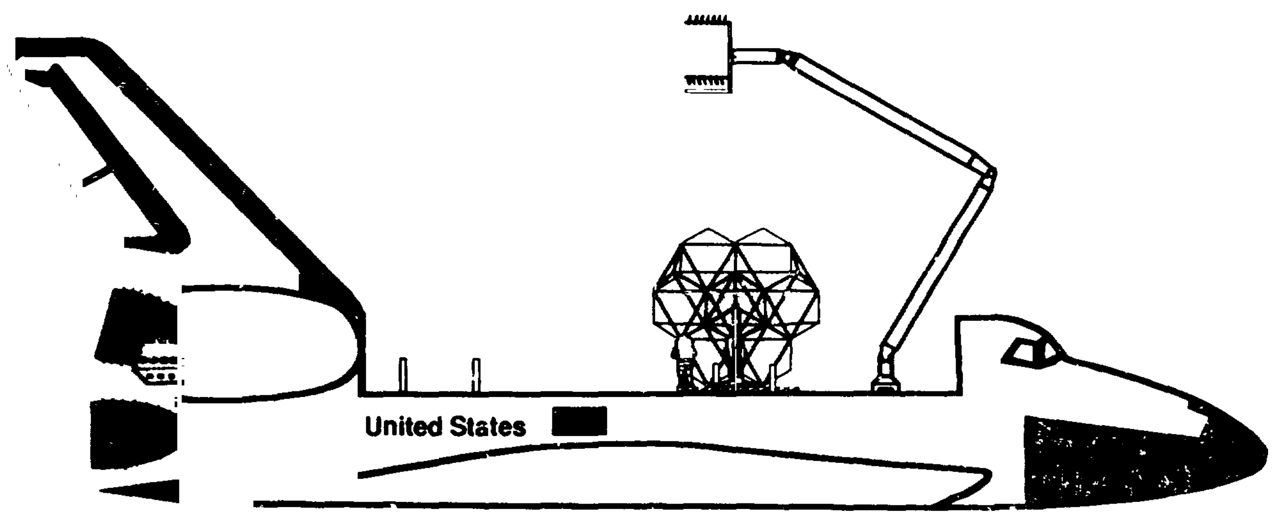


PROBE has two primary objectives: (1) to demonstrat › the in-space construction of a large precision reflector in the Shuttle cargo bay, and (2) to investigate in-space servicing of the reflector following its construction.

PROBE will demonstrate the major assembly tasks associated with on-orbit construction and servicing of a precision segmented reflector by two astronauts in EVA with Remote Manipulator System (RMS) assistance in handling the reflector surface panels. These tasks include construction of the reflector surface support structure (parabolic tetrahedral truss) and attachment of the reflector surface panels including hookup of simulated electrical cables. Although only simulated panels will be used, their external appearance, mass, and overall dimensions will coincide with a baseline configuration.

PROBE OBJECTIVES

- To demonstrate the in-space construction of a large precision reflector in the Shuttle cargo bay
- To investigate in-space servicing of the reflector

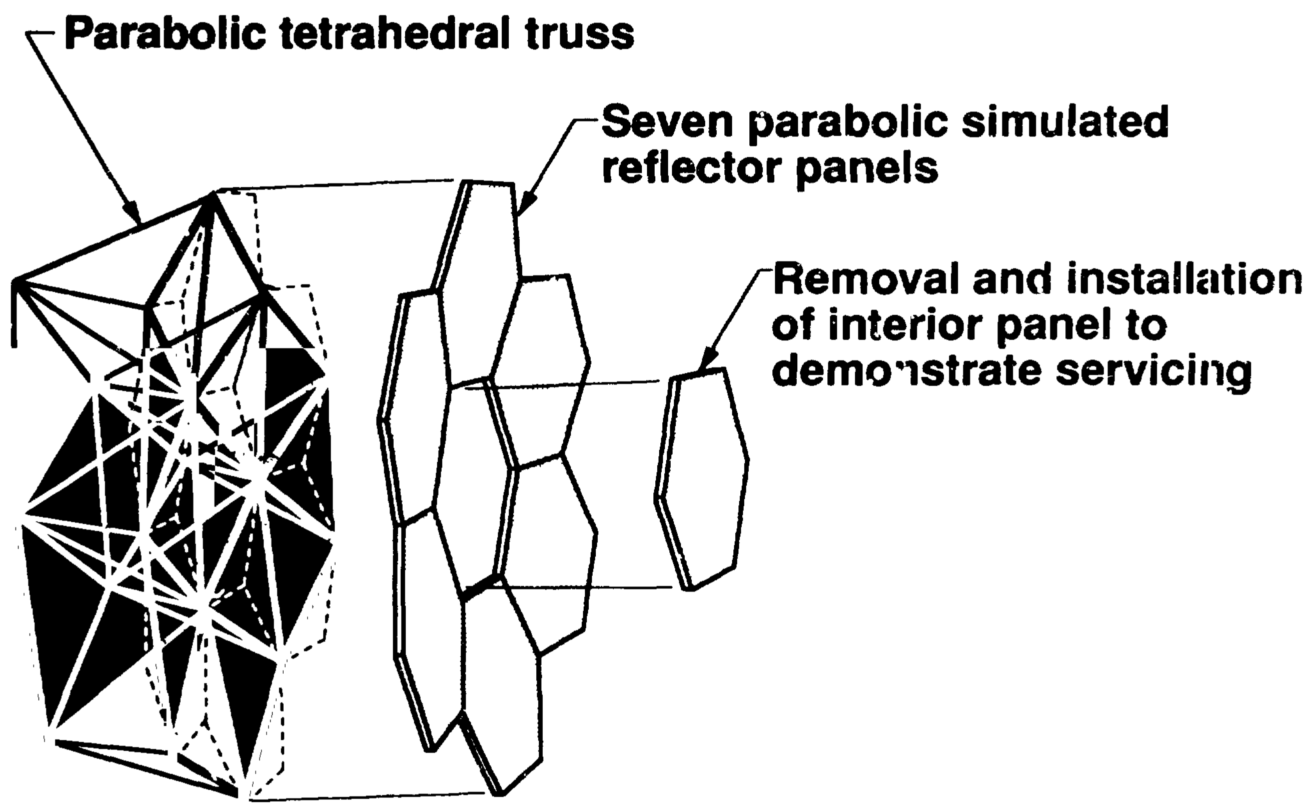


NASA Langley Research Center — Heard 2-22-89

The ***PROBE*** truss consists of 51 graphite-epoxy struts with aluminum end joint fittings for attachment to 18 nodal joints. Since the truss is parabolic, the struts cannot all be the same length, nor are the nodal joints identical. Thus these components will be stowed in canisters in a specified order for astronaut accessibility during on-orbit construction. Seven simulated reflector panels will be attached to the truss. Manual installation of the surface panels and removal of their protective covers will be integrated with the piece-by-piece assembly of the truss rather than accomplished after the truss is fully assembled.

Following assembly, servicing will be demonstrated by installation and removal of a single panel. At the conclusion of these activities the structure will be disassembled and stowed for return to Earth.

TRUSS AND PANELS

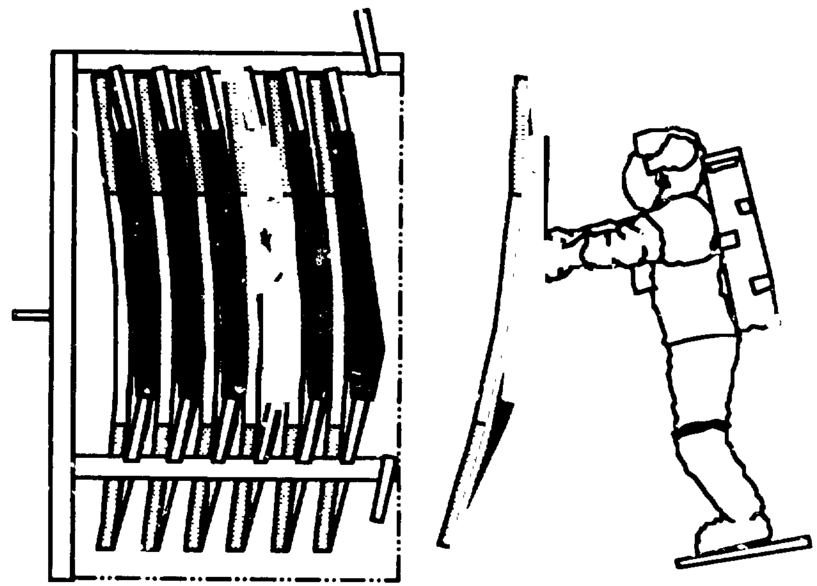


NASA Langley Research Center

Heard 4-24-89

The panels will be stowed in a specified order in a dispenser type canister with a grapple fixture for manipulation by the RMS. The RMS will be used to maneuver the panel canister into proximity of the truss (within arms reach of the EVA astronauts), however, the astronauts will manually remove the panels from the canister and make the final attachments to the truss.

PANEL DISPENSER CANISTER CONCEPT



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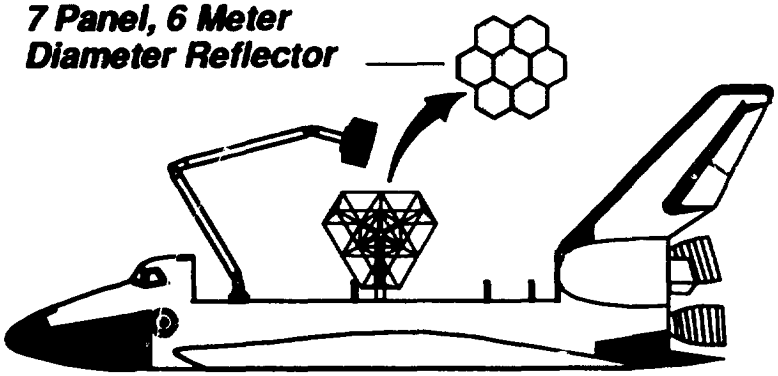
The method of construction used for ***PROBE*** will draw heavily on the techniques used and knowledge gained from the *ACCESS* flight experiment (launched Nov. 26, 1985) in which a 45-foot long truss beam consisting of 93 aluminum struts (4.5 and 6.4 ft in length) and 33 aluminum nodes was manually assembled on-orbit in approximately 25 minutes.

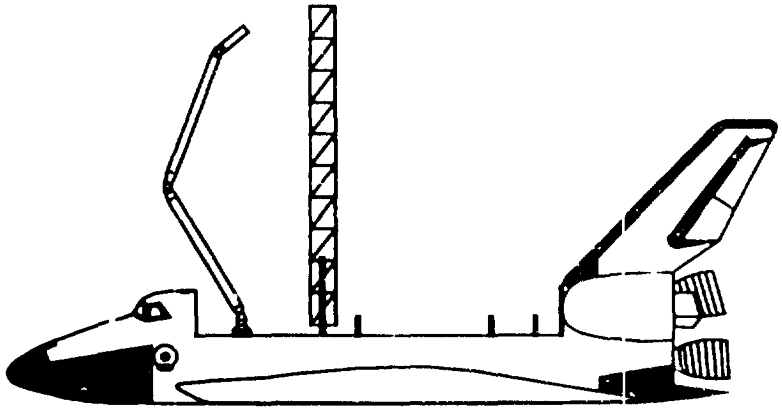
ACCESS

EVA STRUCTURAL ASSEMBLY EXPERIMENT

PROBE is anticipated to be approximately twice as involved as *ACCESS* because of the added integration complexity associated with installation of the panels. As with *ACCESS*, *PROBE* will be assembled on an assembly fixture attached to a pallet in the Shuttle cargo bay. The assembly fixture will consist of a telescoping mast with a turnstile located at its upper end for supporting the truss. The assembly fixture will be manually deployed and operated during construction of the reflector (telescoping and turnstile rotation operations) by the two EVA astronauts, thus no electrical power is required. The astronauts will be required to work from several locations, therefore movable and/or multiple foot restraints will be required.

PROBE APPROXIMATELY TWICE* AS INVOLVED AS *ACCESS*



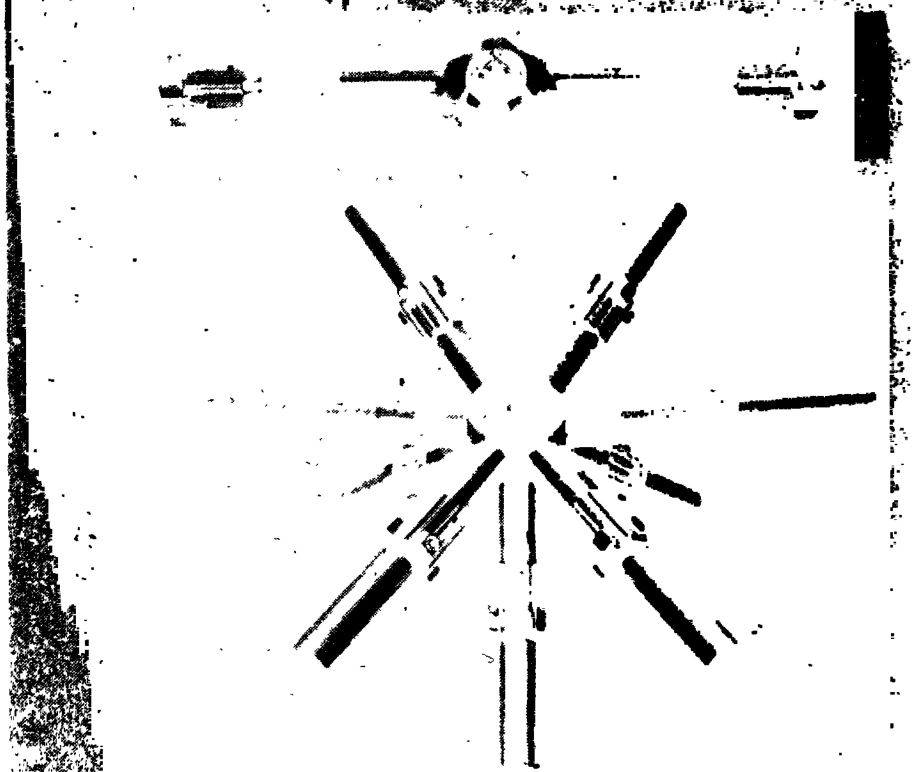


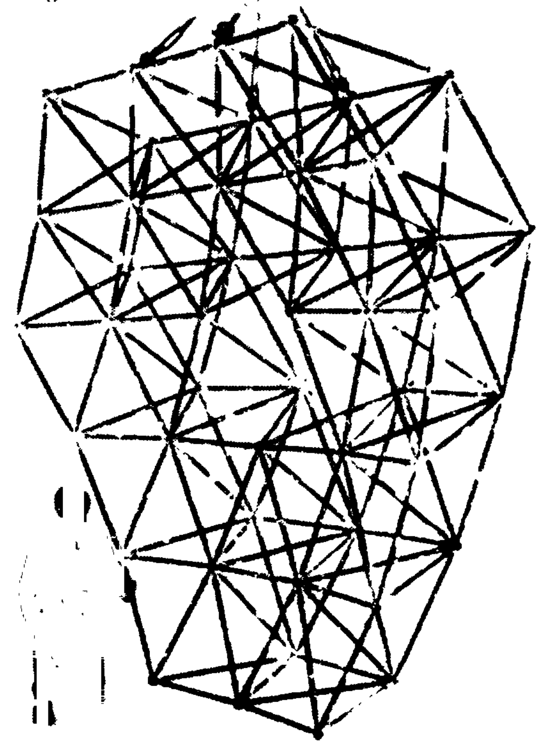
PROBE	*ACCESS*
51 Struts	93 Struts
7 Panels	......
1.5 Hour Assembly	25 Minute Assembly
No Electronics	No Electronics

* *Primarily because of added integration complexity associated with the panels*

The joints that will be used for the *PROBE* truss are similar to the Space Station Freedom baseline joint, although scaled down to be compatible with one-inch diameter truss members. These joints are well developed and have already been used to assemble at Langley a precision parabolic truss consisting of 150 graphite-epoxy struts one inch in diameter. The core struts are nominally 0.8 meters in length. The front and back face struts are of various lengths to produce the parabolic curvature.

PRECISION PARABOLIC TRUSS HARDWARE

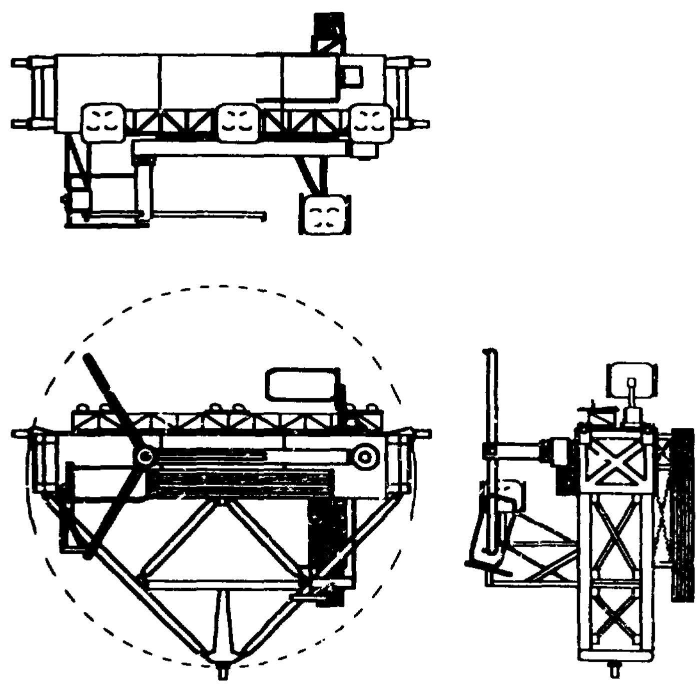




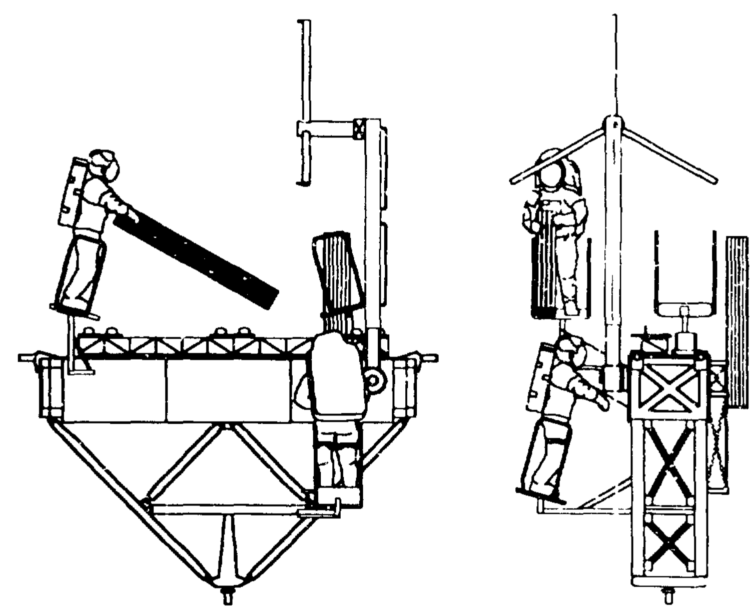
The ***PROBE*** assembly fixture, foot restraints, and strut and node canisters will be supported during launch and reentry on a Mission Particular Equipment Support Structure (MPESS), a standard Shuttle carrier pallet. The panel canister may also be attached to the MPESS or at another location in the cargo bay which is accessible to the RMS. Deployment of the assembly fixture and all other hardware setup required to prepare the worksite for assembly of the reflector will be performed by the EVA astronauts.

WORKSITE

STOWED CONFIGURATION



MANUAL SETUP



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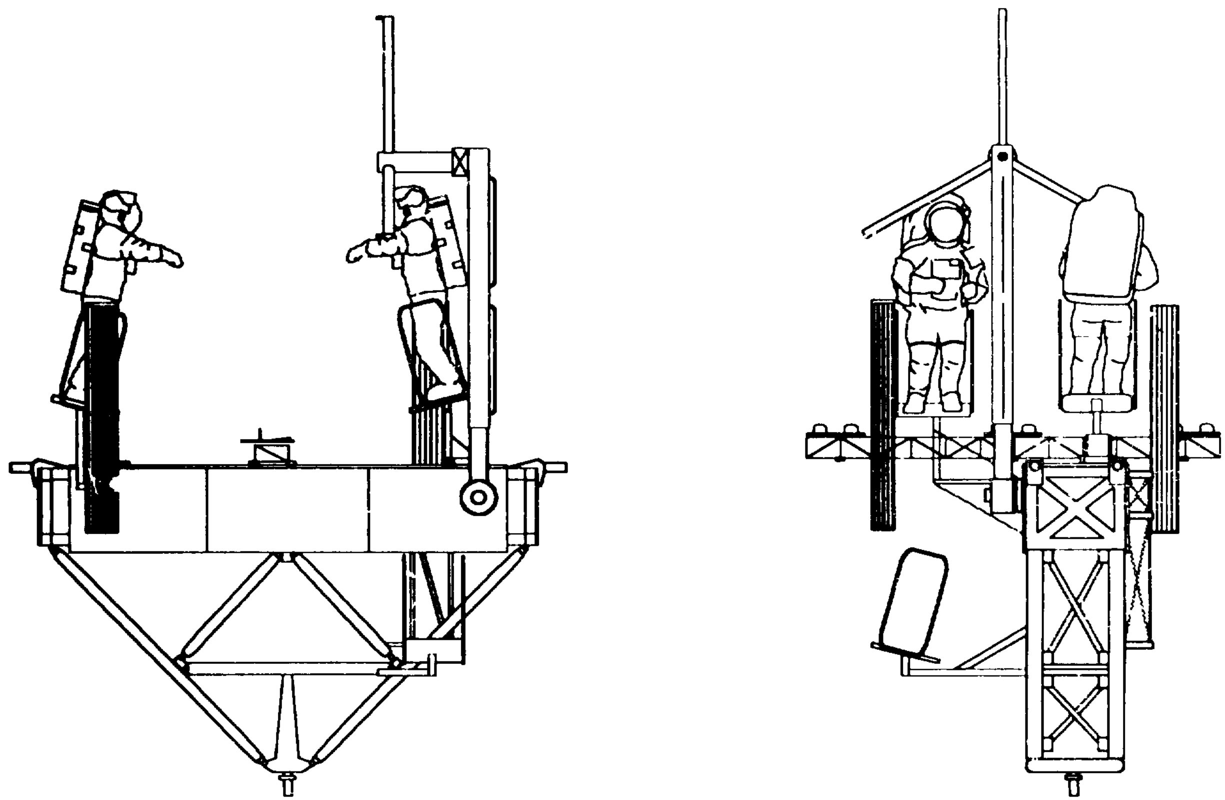
Based on the *ACCESS* experimental results, it is estimated that the worksite can be prepared **for assembly** within 23 minutes following the astronauts exit from the airlock.

WORKSITE READY TO BEGIN ASSEMBLY

00:23:00



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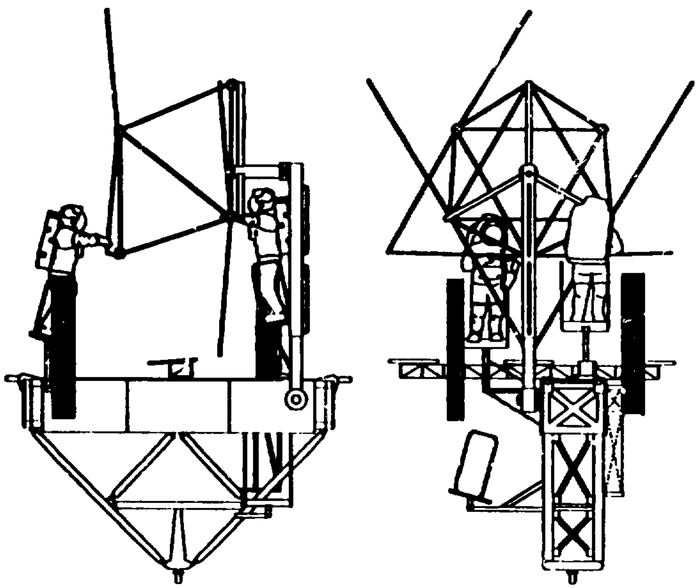
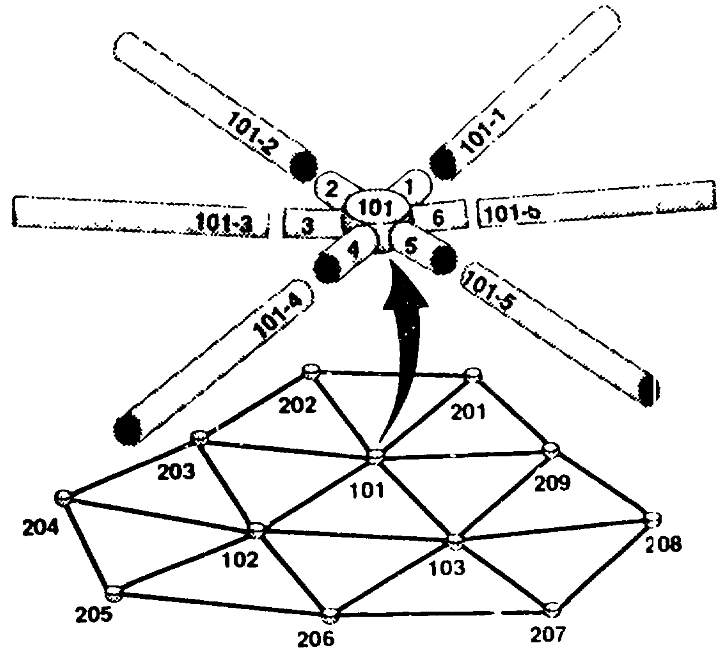
Working from fixed foot restraints the astronauts assemble a segment of the truss on the turnstile. A node/strut numbering scheme has been developed which requires no special training or written instructions. (The time estimates appearing herein are not generated from computer simulations, but based on experimental results obtained from the *ACCESS* experiment and from neutral buoyancy experience in assembling truss structures consisting of similar size components).

ASSEMBLY SEQUENCE

Install Struts & Nodes



00:29:00



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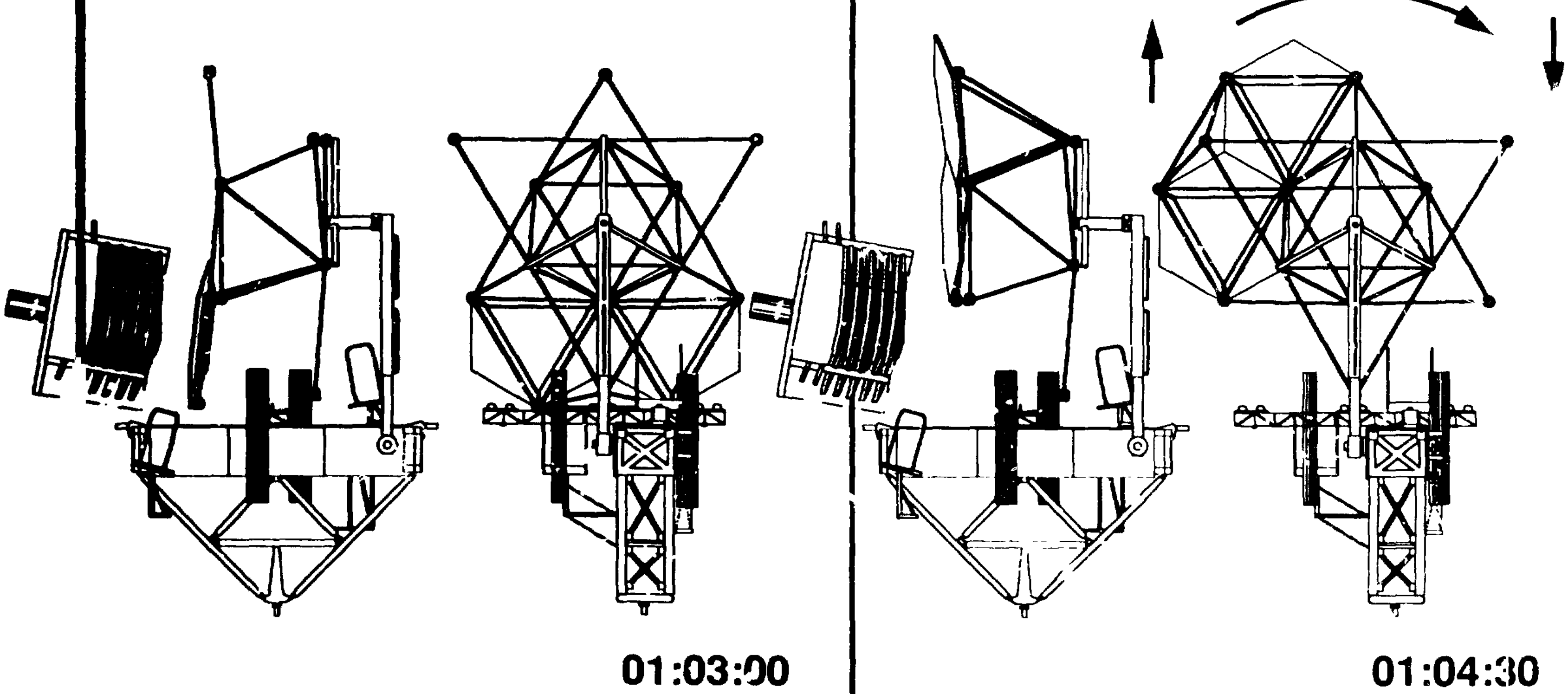
Heard 4-11-89

The RMS will be used to maneuver the panel canister close to the concave surface of the truss. The astronauts working from foot restraints attached to a truss-like catwalk on top of the MPESS will manually remove a panel from the canister, attach it to the truss, and install the additional struts required to stabilize the panel. Two panels will be attached between 120° rotations of the turnstile. A total of six panels will be attached in this manner.

ATTACHMENT OF PANELS



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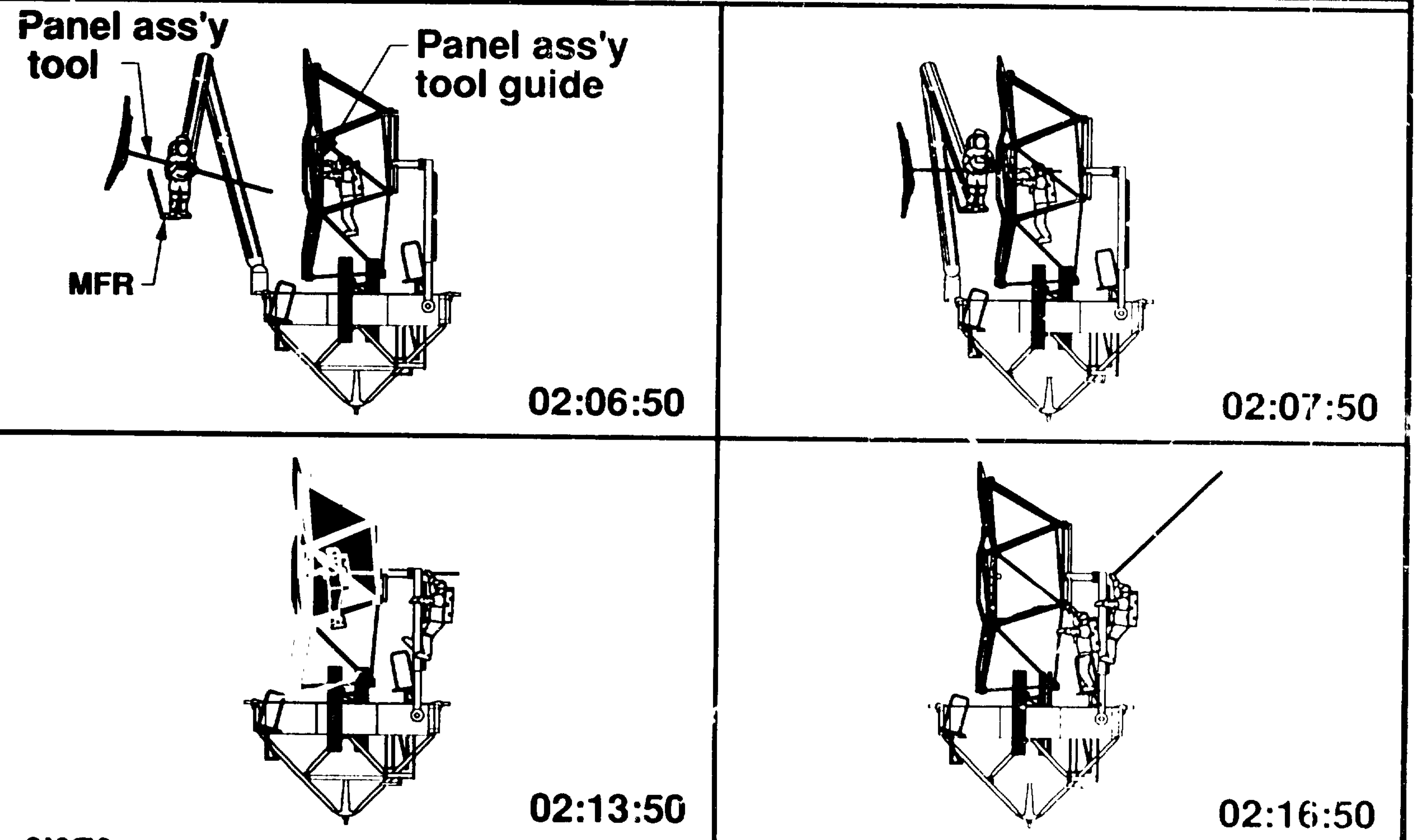
Following assembly, servicing will be demonstrated by installation and removal of a single panel in the center of the reflector. Again, the RMS will be used with an astronaut positioned in the Manipulator Foot Restraint (MFR) to act as a grapple. Two special tools used in this operation are the panel assembly tool and panel assembly tool guide.

SERVICING DEMONSTRATION



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Heard 4/17/89

The complete flight experiment can be completed in one EVA day. The major tasks and estimated time for completion are presented in Table 1, and a summary for the reflector components is presented in Table 2.

PROBE SUMMARY

TABLE 1

TASK	TIME
Worksite Prep	00:23:00
Assembly	01:29:00
Servicing	
Panel Installation	00:25:00
Panel Removal	00:25:00
Disassembly & Stowage	01:29:00
Stow Worksite	00:23:00
Total	04:34:00

TABLE 2

Truss	
No. of struts	51
No. of nodes	18
Mass	93 lbm
Max dimension	19.7 ft
Reflector surface	
No. of panels	7
Area	261 ft^2
Mass	533 lbm
Max dimension	19.7 ft

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Heard 1-8-90

An aluminum planer truss mockup has been fabricated and assembled in the laboratory as an aid to developing the on-orbit assembly procedure for *PROBE*. Three low-fidelity flat panels are also being used in this on-going study.

ORIGINAL PAGE
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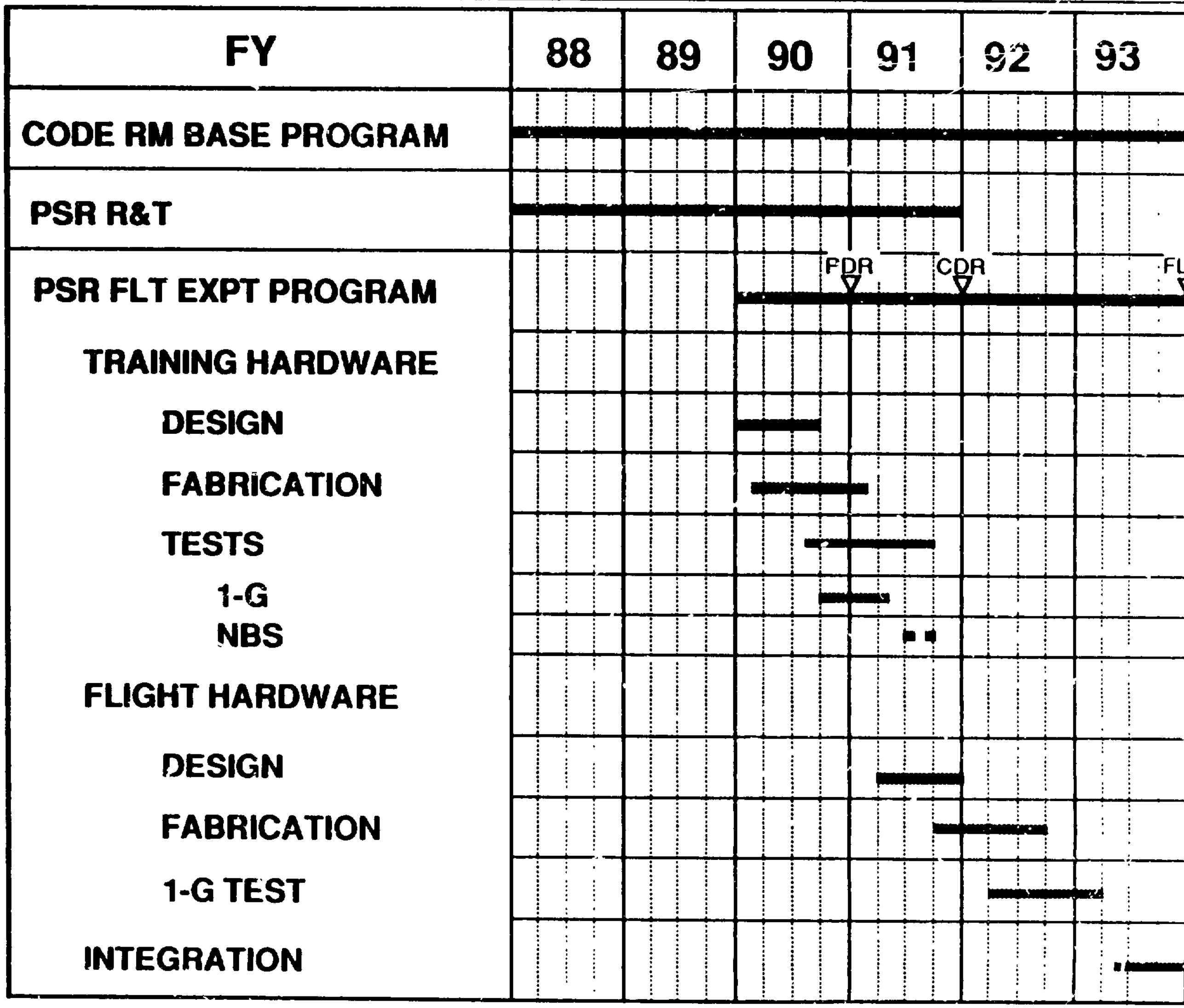
Pending notification of ***PROBE*** go-ahead, plans have been made under base R&T to assemble a parabolic truss and attach reflector surface panel mockups in neutral buoyancy tests.

SCHEDULE



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N93-27842

AUTOMATED ASSEMBLY OF LARGE SPACE STRUCTURES

MARVIN D. RHODES
LANGLEY RESEARCH CENTER

PROGRAM RESEARCH OBJECTIVE

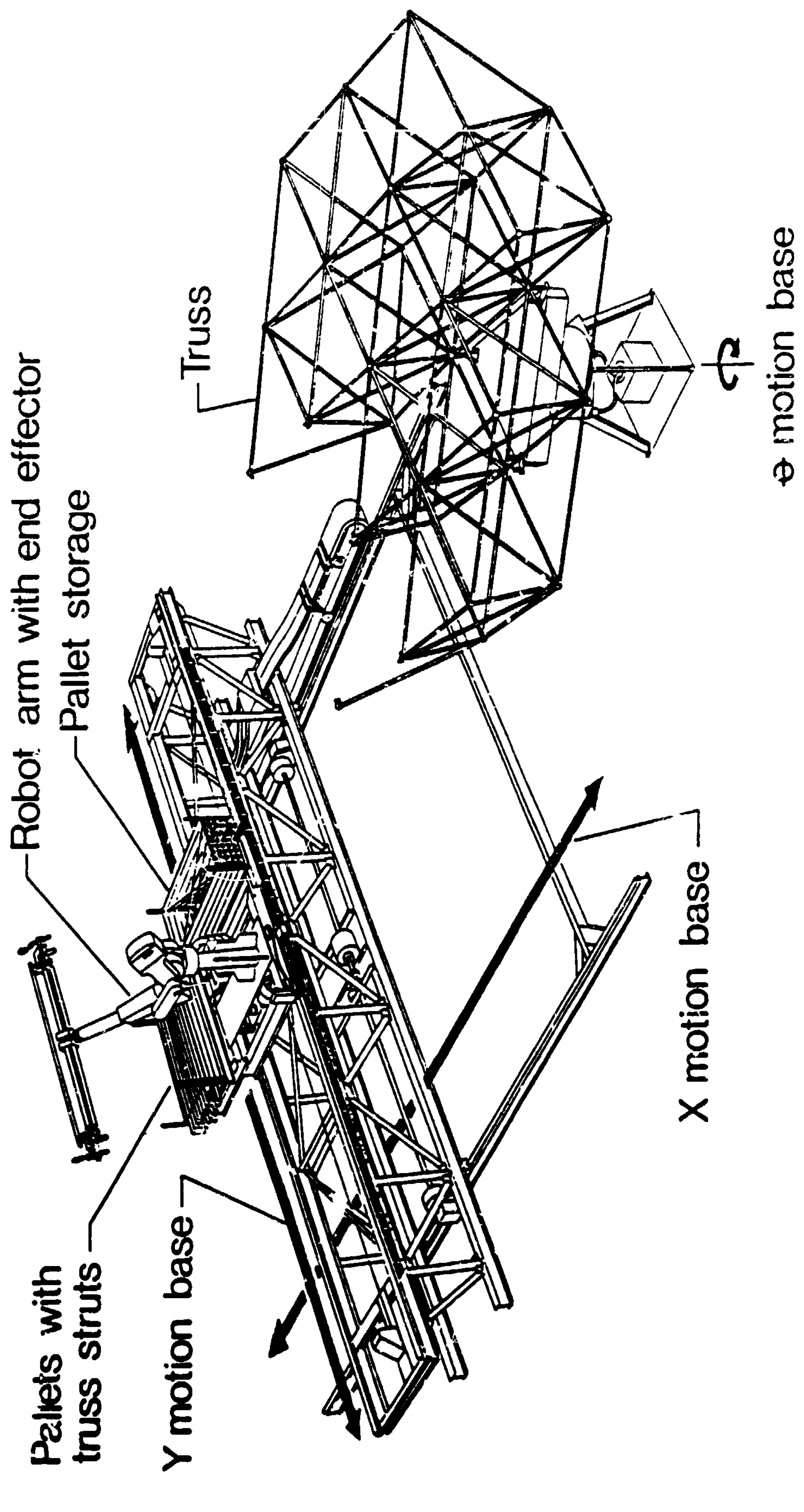
DEVELOP TECHNOLOGY AND DEMONSTRATE THE POTENTIAL FOR AUTOMATED INSPACE ASSEMBLY OF LARGE ERECTABLE STRUCTURES

APPROACH

MERGE EXPERIENCE IN STRUCTURAL ASSEMBLY AND ROBOTICS AT LARC INTO AN INTERDISCIPLINARY PROGRAM WITH FOCUSED EFFORT ON AUTOMATED ASSEMBLY OF A GENERIC STRUCTURAL CONFIGURATION WITH A STANDARD CELL AND BUILD INTO THE SYSTEM THE CAPABILITY TO DO EXPANDED RESEARCH WITH COMPLEX CONFIGURATIONS

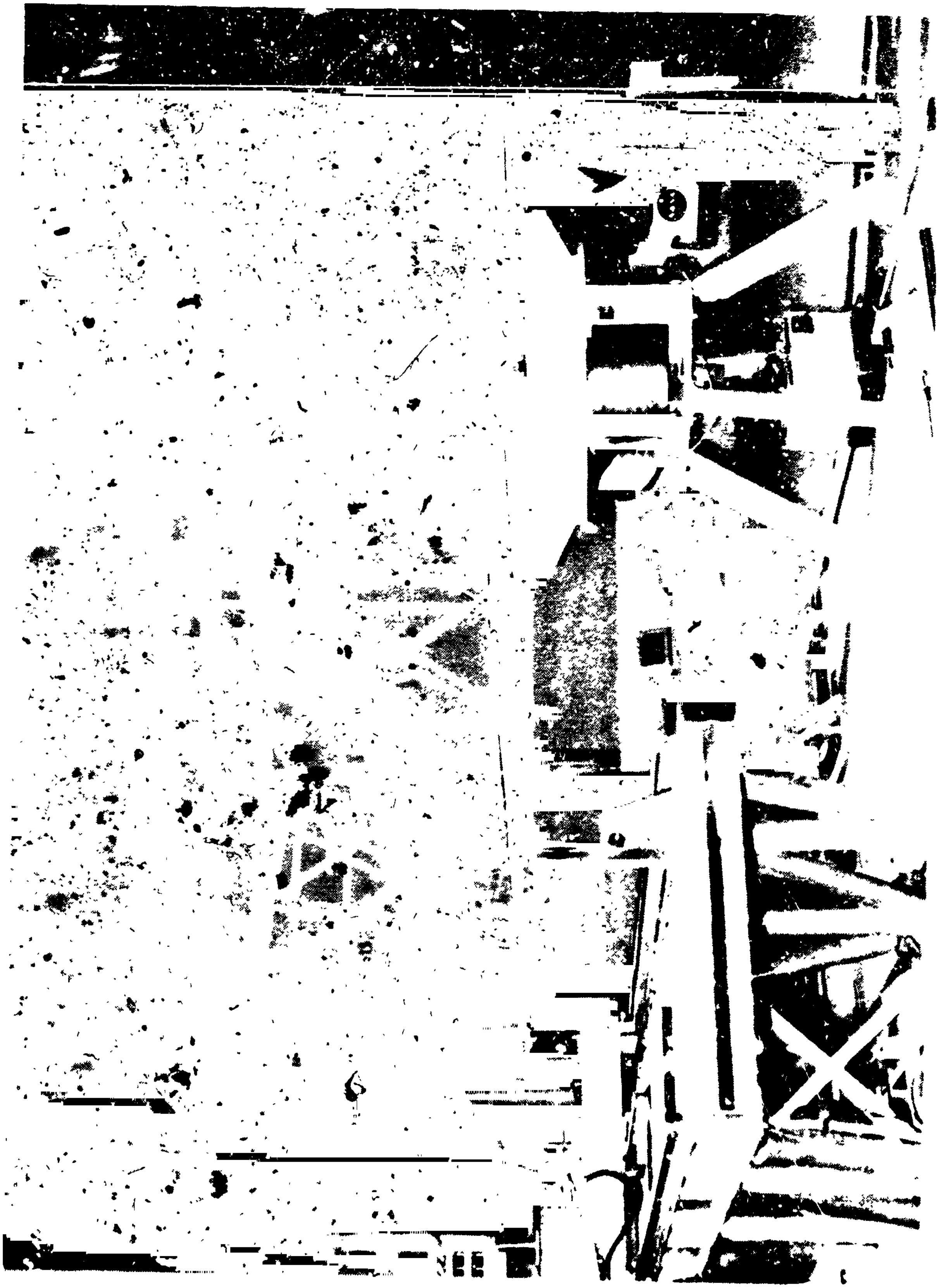
Future space missions such as submillimeter astronomical telescopes and aerobrakes for Mars landers are likely to require support trusses to provide a stiff structure to position and support a large segmented panel surface. The support structure for these missions will involve the assembly of thousands of members and the potential demands on astronauts work time and the potential hazards associated with EVA operations make it imperative to examine alternate techniques for routine structural assembly operations. Therefore, an interdisciplinary program was recently initiated at the Langley Research Center to evaluate the potential for automated in-space assembly. The experience in structural joint design developed over the past several years, was joined with robotics technology to form an interdisciplinary research team to evaluate automated assembly of a regular tetrahedral truss. This truss was selected because it has been proposed as the backbone structure for a number of future missions and it has a simple geometrical configuration that is developed around a standard unit cell. Also the truss construction can be easily expanded to very large systems by simple repetitive operations.

Features of the assembly facility are shown in this sketch. A commercially available robot arm is mounted on a carriage system to position the robot in an X-Y reference frame. The truss is assembled on a rotating motion base near the end of the X carriage system. The struts used in the construction of the truss are stored in pallets that are mounted immediately behind and within easy reach of the robot arm. As the pallets are emptied they are moved to a pallet storage rack. This facility was designed around the use of existing components and fabricated from traditional structural shapes so that the research program could be initiated quickly and the system could be modified as experience dictates. This facility is intended to be a research development tool as opposed to a brass-board space flight system.


Truss
Robot arm with end effector
Pallet storage
Pallets with truss struts
Y motion base
X motion base
θ motion base

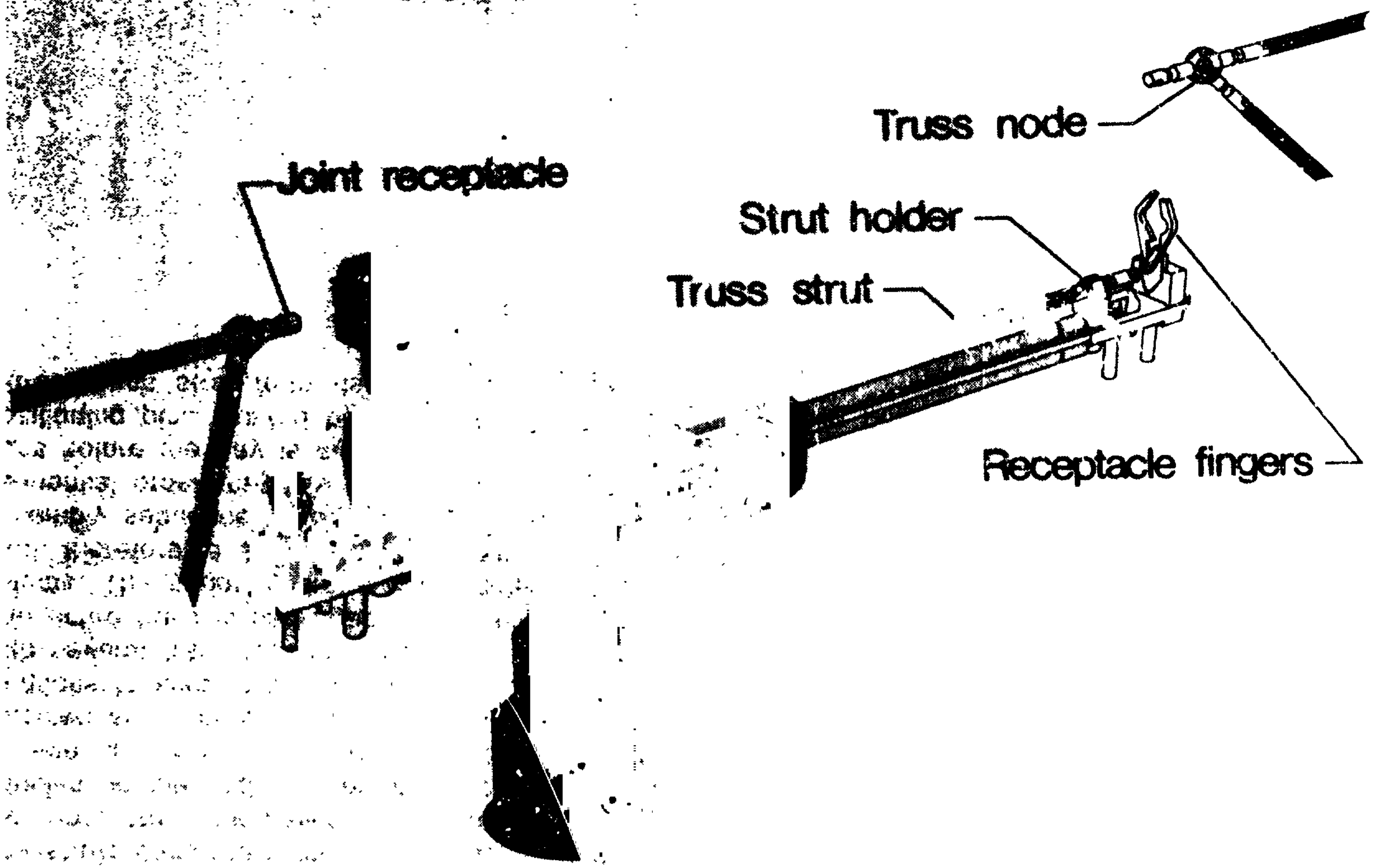
A photograph of some of the facility components are shown in this figure. The truss has tubular strut members that are 2 meters long and 2.6 cm in diameter. There are 102 struts in the completed truss configuration, however, the facility is of adequate size to enlarge the test truss to 252 members. The strut tubes are graphite/epoxy with a wall thickness of 2.03 mm (0.080 in). They were fabricated on a mandrel from unidirectional prepreg which was preplied at +/- 10 deg before being rolled on the tool. The truss joints are aluminum and they were designed to provide structural preload and linear load deflection response through the connection interface.

The rotating motion base and the X and Y carriages are motor driven and have sensors to position the respective components at operator defined locations. All of these drive systems use cables wrapped around drum pulleys to minimize system backlash and freeplay. The motion base systems were stiffness designed so that deflections introduced from unbalanced assembly or from forces applied by the robot arm would not adversely affect construction operations.

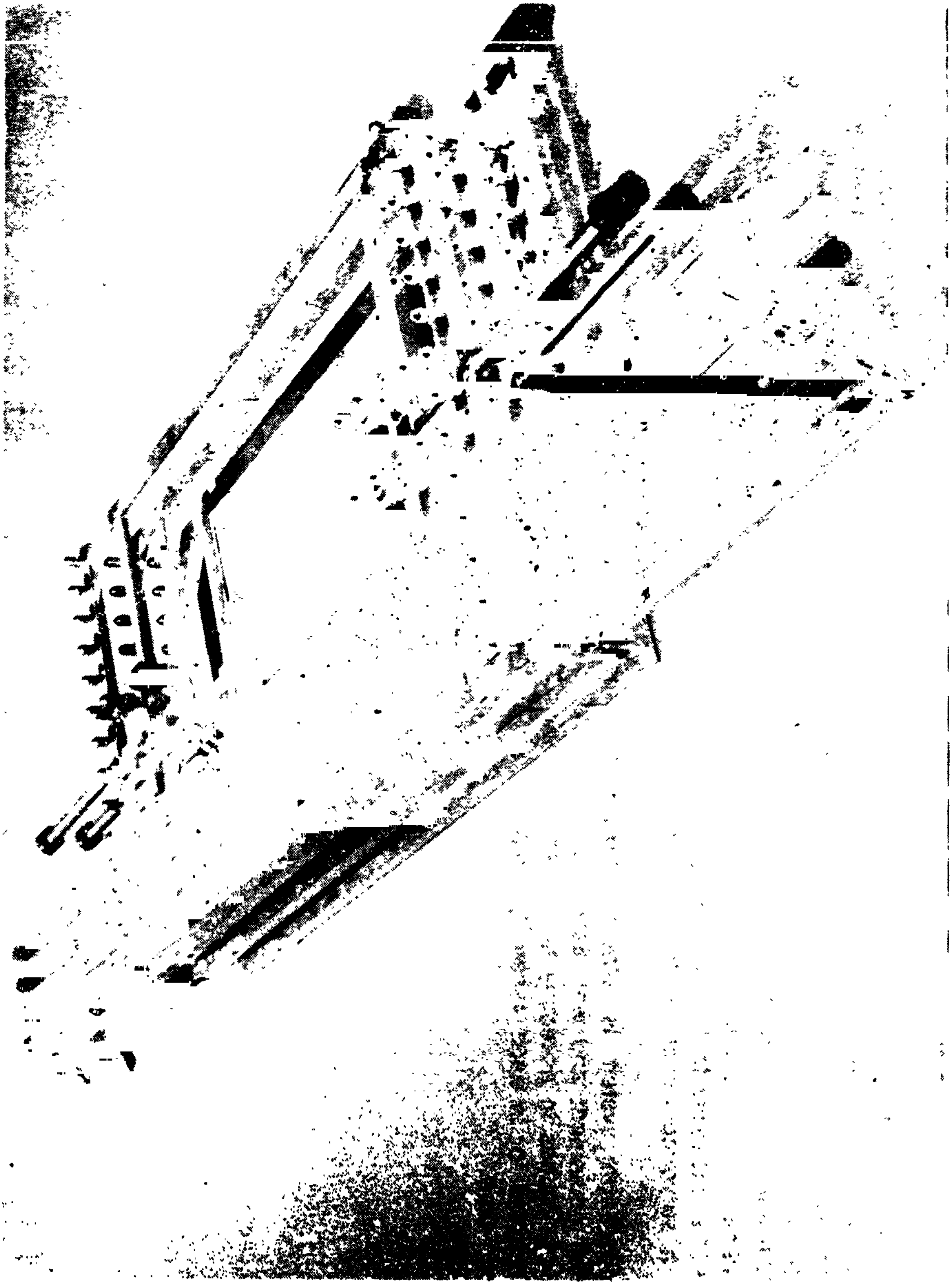


The end-effector is a specially designed tool that is dedicated to the task of grasping the struts in the pallets, holding the strut as the arm moves into position, grasping joint receptacles on the nodes, inserting the strut into the nodes, locking the joint, and then releasing the member. The fingers on each end of the end-effector grasp the joint receptacle and are seated in the groove when closed. These fingers are designed to capture the receptacle at any location within a 2.5 cm diameter by 1.5 cm long cylindrical envelope, and will move the nodes of members that are connected together as a frame into the correct position for strut insertion. This feature compensates for misalignment caused by gravity or bowing of the strut graphite tubes. It also secures all components so that drag or small misalignments will not restrict the insertion operation. Having grasped the receptacle, the end-effector inserts the strut in the joint and a motor powered nut driver locks the strut in place. The total operation of the joint and the end-effector were designed as a coordinated unit, as opposed to designing one component such as the joint and then designing an end-effector to make it operate. The end-effector is designed to permit operation either with a node preattached to the strut, or to insert a strut into nodes already assembled on the truss.

ROBOT END EFFECTOR



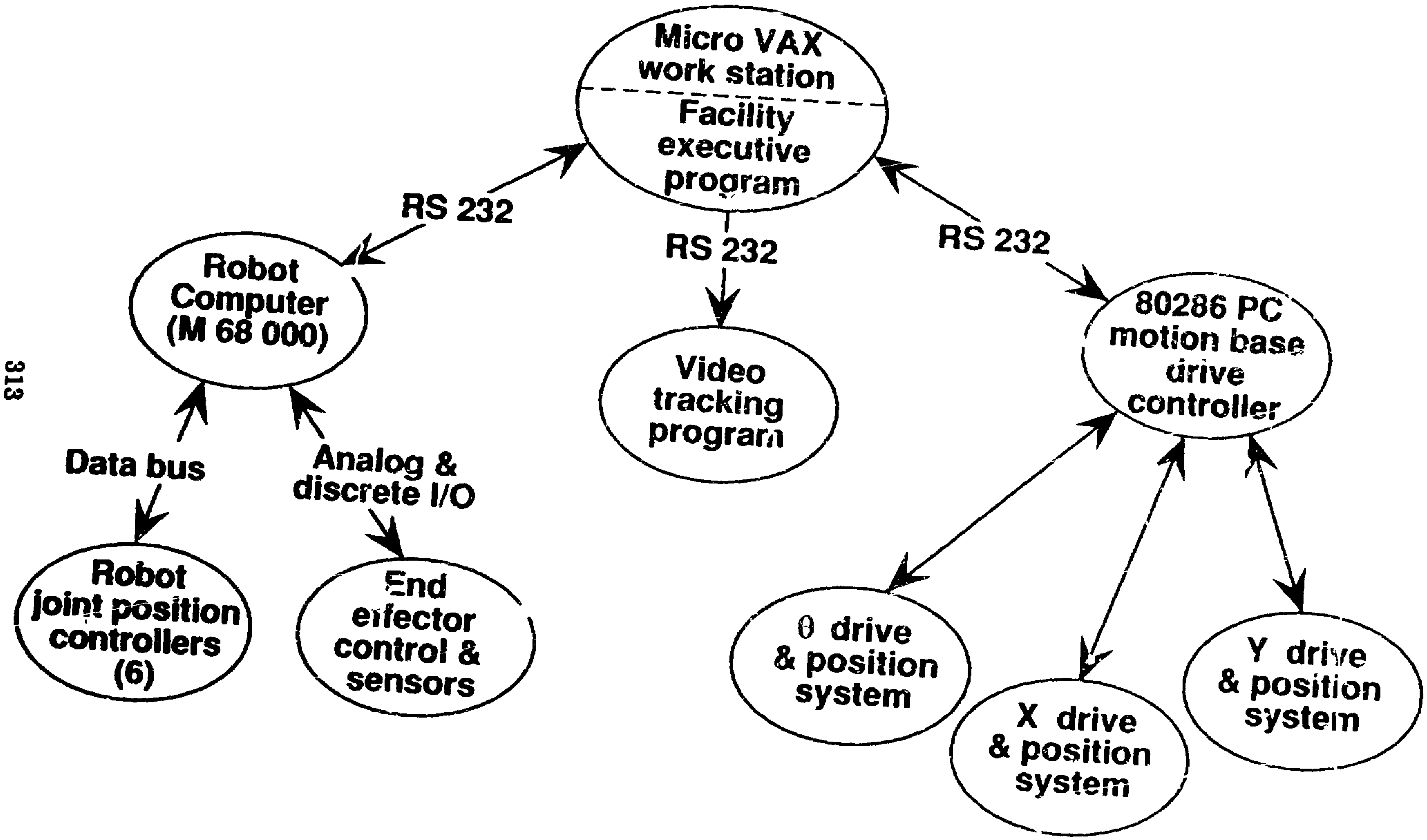
The struts comprising the truss structure are mounted in pallets that are held in a rack behind the robot arm. The pallets are structural frames fabricated from aluminum angle. Each pallet has handles on the ends to permit the strut holder on the end-effector to move it to the pallet storage rack. Each pallet will hold up to 13 struts and the nodes are preattached to one end of selected struts before assembly begins. The struts are placed in the pallets at preselected locations to accommodate efficient packaging. The complete truss can be packaged in 9 trays with several tray locations unused to accommodate selective placement of nodes in the pallets. The entire truss is packaged in an envelope which is less than 1.4% of the fully erected truss volume. The nodes interfere with each other if they are placed closer together than every fourth strut, therefore, a special arrangement of the nodes had to be devised and coordinated with the assembly sequence. The struts are not necessarily selected for insertion in the truss in the sequential order they are arranged in the pallets. However, all struts in a tray are inserted in the truss before the tray is moved to the storage rack. Spring loaded pin plungers in the side of the positioning pins located between struts hold the struts in the pallet and a force is required to extract each strut from its storage location.



Several computers are used to monitor and control the operations of the assembly facility. The function of these various computers is illustrated in the figure. The system is controlled by an executive program executed by a microVAX workstation. The executive program communicates with the other computers, a Motorola 68000 based unit and an 80286 based PC, by transmitting ASCII code through RS232 lines. Output commands are transmitted from both of these lower level systems directly to stepper drive motors and encoder position sensors. The robot computer also has the capability to handle analog and discrete input and output signals and is, therefore, used as a servo controller for the end-effector.

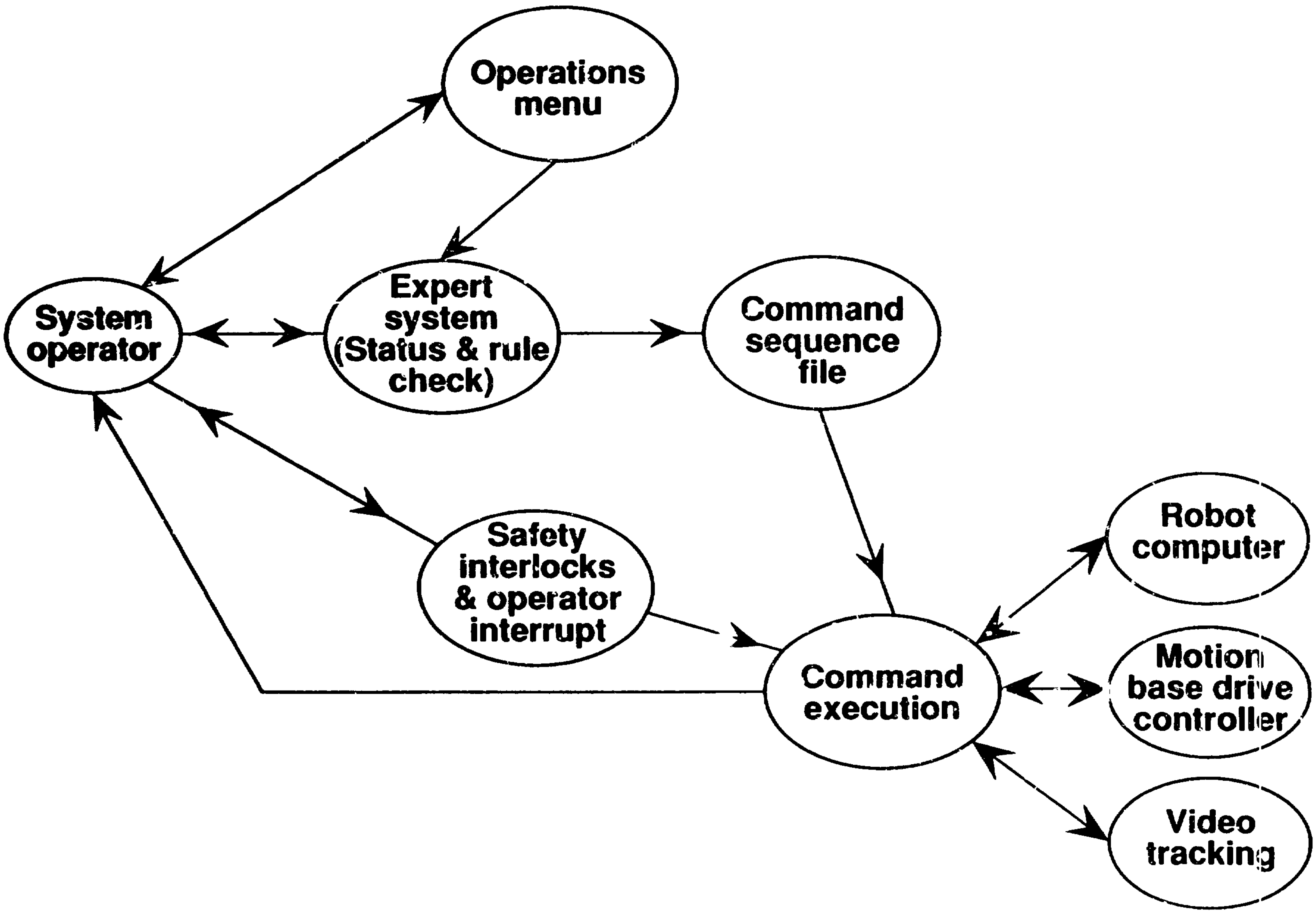
This control system is relatively slow and unsophisticated, however, it incorporates all off-the-shelf equipment and was assembled rapidly so that operational testing could begin without delay. Pauses in assembly time associated with the transfer of program commands can be accounted for in each assembly operation. Parallel system operation may be incorporated at a later time.

FACILITY COMPUTER CONTROL SYSTEM



The assembly facility executive program operates from the microVAX workstation and the operation is shown schematically in the figure. The system operator selects the desired assembly function from a menu of preprogrammed operations. The selected menu function is directed to the expert system which stores in memory the preceding operation and determines what changes in the current hardware configuration are required to perform the new menu selection. The hardware configuration status includes the truss struts and their location, the state of the end-effector, and the position of the motion bases. If the selected operation can be performed, the system notifies the operator and checks the facility safety interlocks. The expert system then generates the command sequence file required to perform the selected menu function and the commands are directed to the appropriate sublevel computer in sequential order. As the commands are executed the operator is notified by the executive program. The operator monitors the operations as they occur by a video surveillance system. If a failure occurs the operator has a menu from which to select corrective options and he will be permitted to override some noncritical fault indicators. All anticipated and experimentally defined failures are being incorporated into the operator menus. Those not listed can only be performed by directly accessing the appropriate sublevel computer.

COMPUTER EXECUTIVE PROGRAM



The research development plan for automated assembly of large space structures is shown in the figure. The program outline proceeds from fairly simple pick and place operations where robots are traditionally applied in terrestrial applications to complex operations for which sensors and controls play a major role. The initial assembly uses operator "taught" paths and defined locations that require the high level of repeatability built into the control system of most robot arms. By having redundant degrees of freedom in the assembly motion base system the entire 102 member truss structure can be assembled by "teaching" the paths and positions of approximately 12% of the members. Also the current end-effector is a special purpose tool for assembling trusses of this size. Expanded operations will focus on the design of end-effectors which can perform the assembly of curved trusses where many different length members are required and the same end-effector can be used to attach payloads during truss assembly. Finally, any mechanism that operates at a remote and inaccessible location where collision can cause considerable damage will require a complex 3D graphics simulation with path planners and sensor guidance.

Automated Assembly of Large Space Structures

Project Development

"Dumb" assembly of planar truss using taught points & dedicated robot positions

⇘

Expanded truss assembly with payloads, panels, sensor guidance and graphics simulation

⇘

Curved truss structure, system dynamics and coordinated motion

⇘

"Smart" assembly of complex integrated system with sensor guidance and collision avoidance path planner

To support the logical progression of the research program a number of activities listed on the accompany chart are planned for near term development. Some of these activities, such as attachment of panels, will expand the system capabilities while others, like the path planner and sensor guidance, will significantly increase reliability. These activities will benefit many proposed missions which require in-space assembly. This focused program provides as excellent opportunity to develop a much needed technology base.

Automated Assembly of Large Space Structures

Current System Development Plans

Panels and Payloads For Attachment To Truss

Evaluate Suitability Of System For Assembly Of SS Solar Dynamic Reflector

Develop Path Planner For First Level End Effector Positioning

Incorporate Sensors For Intermediate End Effector Positioning

Develop Graphics Simulation Of System To Predict & Monitor Operations

Incorporate Microprocessor Into End Effector Operation

Many useful technical observations in automated assembly have been developed from the limited research conducted to date. Several of these are highlighted on the accompanying chart. The motion base hardware and truss structure were stiffness designed so that gravity induced deflections would not adversely affect assembly operations, especially since only minimal sensor feedback and no sensor guidance was incorporated. The passive guidance features designed into the truss joints and end-effector work well to direct entry of the struts into the correct assembly and capture position.

It was anticipated during the hardware design phase that the combination of arm positioning accuracy, motion base positioning accuracy and strut passive guidance features would be adequate for all assembly operations. However, it became clear very early in the test assembly phase that small positioning errors cause large loads due to the high stiffness of both the truss and the motion base support system. Therefore a force/torque load cell was inserted between the robot arm and the end-effector and final positioning of the end-effector is accomplished by repositioning the robot arm to null out the measured loads and moments. Final positioning of the robot reduces the loads to under 0.8 lbs and the moments to under 5 in-lbs.

During the planning phase it was also anticipated that assembly of the truss joints could be accomplished by simply using the robot arm to push the strut joint directly into the receptacle on the node, rather than capturing the receptacle and having the end-effector insert the strut. Tests conducted to date have shown that the use of the arm to push the strut into place simply would not have worked because small misalignments and friction will push the receptacle aside. Additional discussions on these and other findings will be included in planned publications.

Automated Assembly of Large Space Structures

Program Findings

Precision and Stiffness Of Truss & Carriage System Adequate For "Dumb" Assembly Operations.

Passive Guidance Designed Into System Necessary & Adequate To Correct Positioning Errors.

Force/Torque Load Cell Necessary For Correction Of Cumulative Error.

Insertion Of Strut Into Captured Receptacle Provides Positive Assembly Technique.

Robotic Structural Assembly Must Be Under Computer Control. Difficult For System Operator To Remember All Operations Required For Assembly Of Even Simple Structure.

Preliminary Results Indicate Assembly Times Of 2-5 Minutes/ Strut With Current Operation. Faster Times Achievable With Coordinated Motion & End Effector Microprocessor.

C-4

The large number of struts necessary for the support trusses required for future space missions such as submillimeter astronomical antennas and the Mars aerobrake make it imperative to examine alternate techniques for structural assembly. Due to the repeatability of the members in these trusses, automation using a robot arm for the structural assembly is a natural extension of the traditional pick and place operations for which robots are used in terrestrial applications. The current research also provides a focused effort to expand the capabilities of this automated operation to develop other space assembly methods. However, automation should be considered during the concept development and hardware design phase of a proposed operation and not as a retrofit after the program is well underway.

Automated Assembly of Large Space Structures

Conclusions

Structural Assembly Provides Outstanding Focus For Space Automation- Fundamentally A Pick And Place Task.

No Major Problems Have Been Encountered That Would Indicate Automated Structural Assembly Is Not A Viable Option For In-Space Construction.

Automation Should be Considered In Initial Design And Not As A Retrofit Operation.

Thermal Control System

Level III

Subsystem Presentation

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N93-27843

THERMAL SYSTEMS

J. E. Rogan

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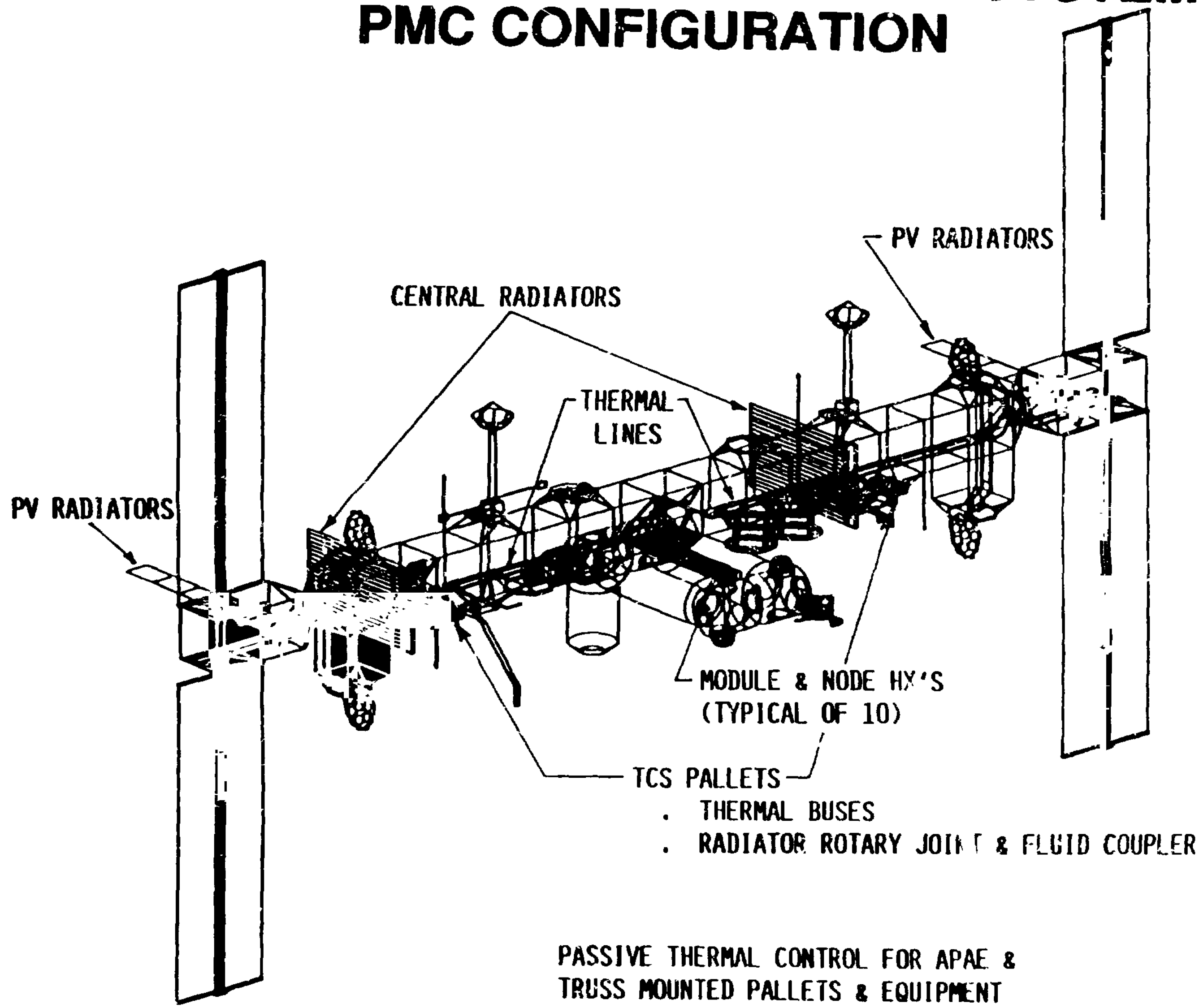
THERMAL CONTROL SYSTEM

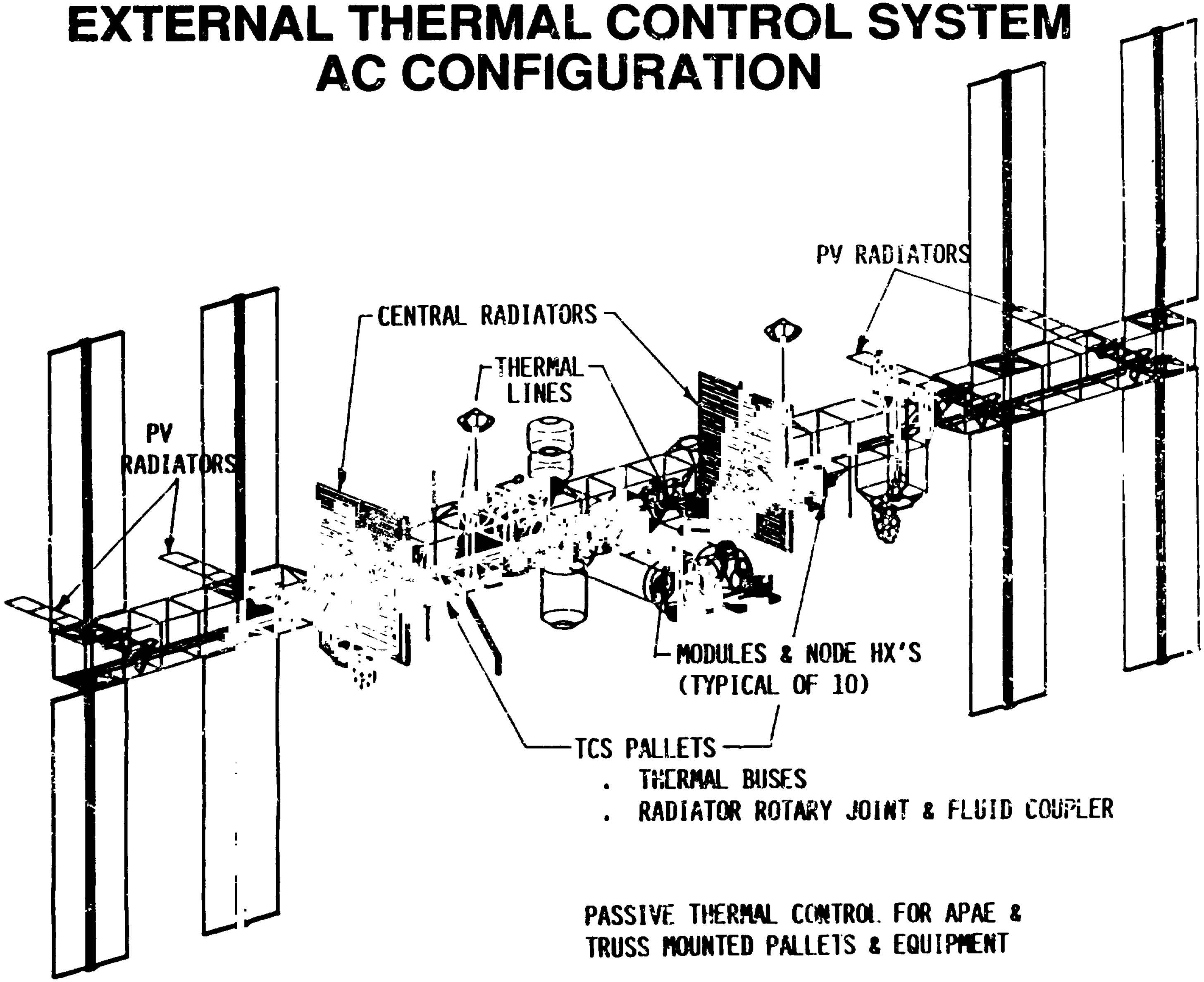
BASELINE CONTENT	REBASELINE PMC	REBASELINE AC
External ATCS		
• Central Radiators (2-Phase Ammonia)	Same (erect only as required)	Same
• Central Thermal Bus (2-Phase Ammonia)		
–Modules and Nodes	Same	Same
–Truss Mounted Pallets	Passive	Passive
Internal ATCS for Pressurized Nodes and Modules (water)	Same	Same
APAE ATCS for Truss-Mounted Payloads	Passive	Passive
PVATCS (1 Phase Fluid and Deployable Radiators)	Same	Same

EXTERNAL THERMAL CONTROL SYSTEM
PMC CONFIGURATION



PASSIVE THERMAL CONTROL FOR APAE &
TRUSS MOUNTED PALLETS & EQUIPMENT

EXTERNAL THERMAL CONTROL SYSTEM
AC CONFIGURATION



PASSIVE THERMAL CONTROL FOR APAE &
TRUSS MOUNTED PALLETS & EQUIPMENT

Space Station Freedom

McDonnell Douglas • GE • Honeywell • IBM • Lockheed

EXTERNAL THERMAL CONTROL SYSTEM REQUIREMENTS

Functional Requirements

- Waste heat acquisition/transport

Performance Requirements

- Collect waste heat from each pressurized element or carrier
- Size for 37.5 kW (PMC) and 75 kW (AC) Plus electrical conversion losses, metabolic and environmental heat loads
- Accommodate modular growth, on-orbit assembly
- Provide simple user interface and location flexibility
- Low and moderate temperature loops (35°F and 70°F)
- Quiescent operation (10% of full load)
- Leak detection, isolation, and repair

EXTERNAL THERMAL CONTROL SYSTEM REQUIREMENTS (CONT.)

Functional Requirements	Performance Requirements
■ Heat rejection	● Accommodate modular growth, on-orbit assembly ● Limited degradation due to damage or failure ● Replaceable radiator
■ Truss mounted pallets and equipment, APAE and Structures	● Passive thermal control
■ APAE payloads	● Provide own independent thermal control

IMPLEMENTATION APPROACH

- Truss mounted pallets and equipment, APAEs and structures - passive thermal control
  - Insulation and coatings
    - Multi-layer high performance insulations
      - Utility distribution lines
      - Resource pallets
      - Airlock
      - Mobile Transporter
      - APAE/payload (WP-3)
      - Modules (WP-1)
      - Nodes (WP-1)

IMPLEMENTATION APPROACH
(Continued)

- Selective absorptivity/emissivity optical surface coatings
  - Radiators
  - Truss
  - Resource pallets
  - APAE/payload (WP-3)
  - Modules (WP-1)
  - Node (WP-1)
- Heaters
  - Electrical radiant-type or conductive
    - Utility distribution lines
    - Propulsion Pallet
    - Mobile Transporter
    - APAE/payload (WP-3)

IMPLEMENTATION APPROACH
(Continued)

- Isolators
  - Low conductivity material
    - Mobile transporter components
    - Airlock
    - Resource Pallets
    - APAE/payload (WP-3)
- Passive Radiators
  - Structural surface area viewing space
    - Resource pallets
    - Mobile Transporter
    - Antennas and cameras
    - APAE/payload (WP-3)

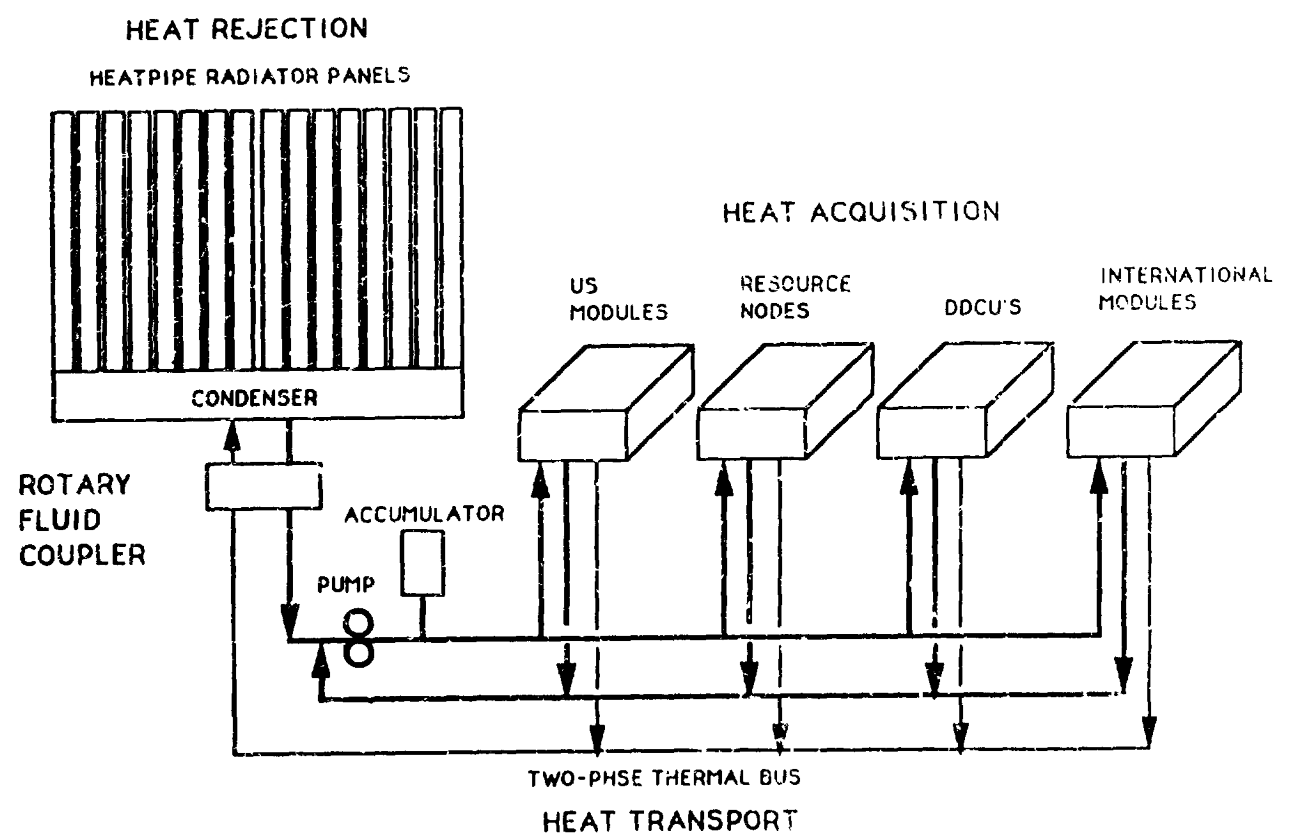
IMPLEMENTATION APPROACH
(Continued)

- **Heat Rejection**
  - Individual radiator elements incorporating self-contained, high capacity heat pipes
    - Each element completely independent of all others
    - Facilitates easy handling for on-orbit assembly
    - Allows interfacing radiator with transport circuit through non-invasive technique
    - Allows replacement of elements to maintain indefinite life

IMPLEMENTATION APPROACH
(Continued)

- Heat acquisition and transport
  - Thermal bus applies heat pipe technology to heat transport
    - Liquid to user interface evaporated. Vapor to radiator interface for condensation
    - All equipment receives the same temperature regardless of location in the circuit
    - Phase change process allows approximately 50 times less fluid to be circulated
- Rotary fluid coupler
  - Allows articulation of radiator to minimize area

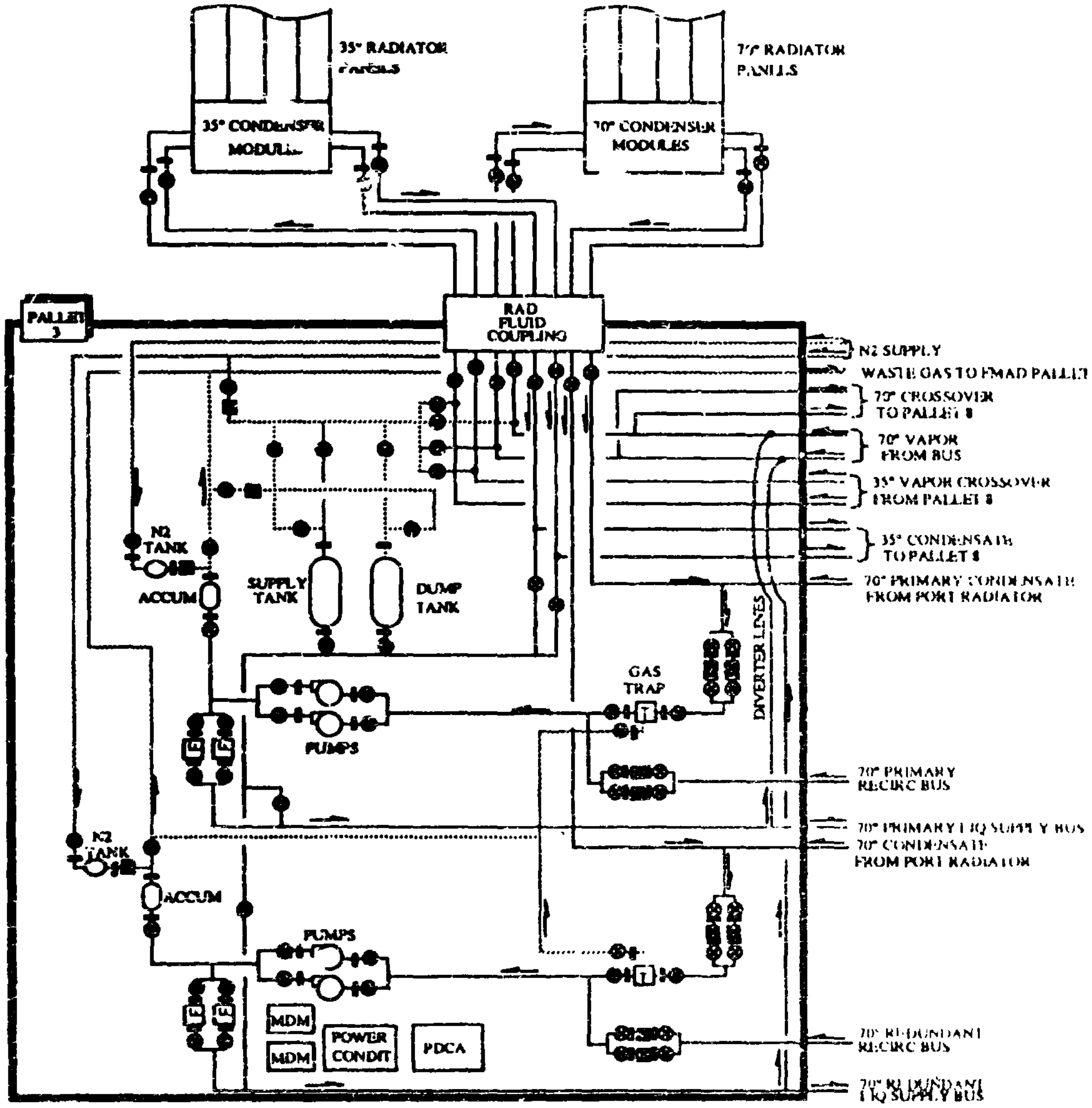
EXTERNAL THERMAL CONTROL SYSTEM



- 35 °F AND 70 °F TEMPERATURE LOOPS
- BOTH LOOPS REDUNDANT
- BOTH TEMPERATURE LOOPS SERVICE PORT AND STARBOARD SIDES OF SSF

LMSC PALLET 3 EQUIPMENT

(FOR CONCEPT EVALUATION ONLY)



TCS EQUIPMENT

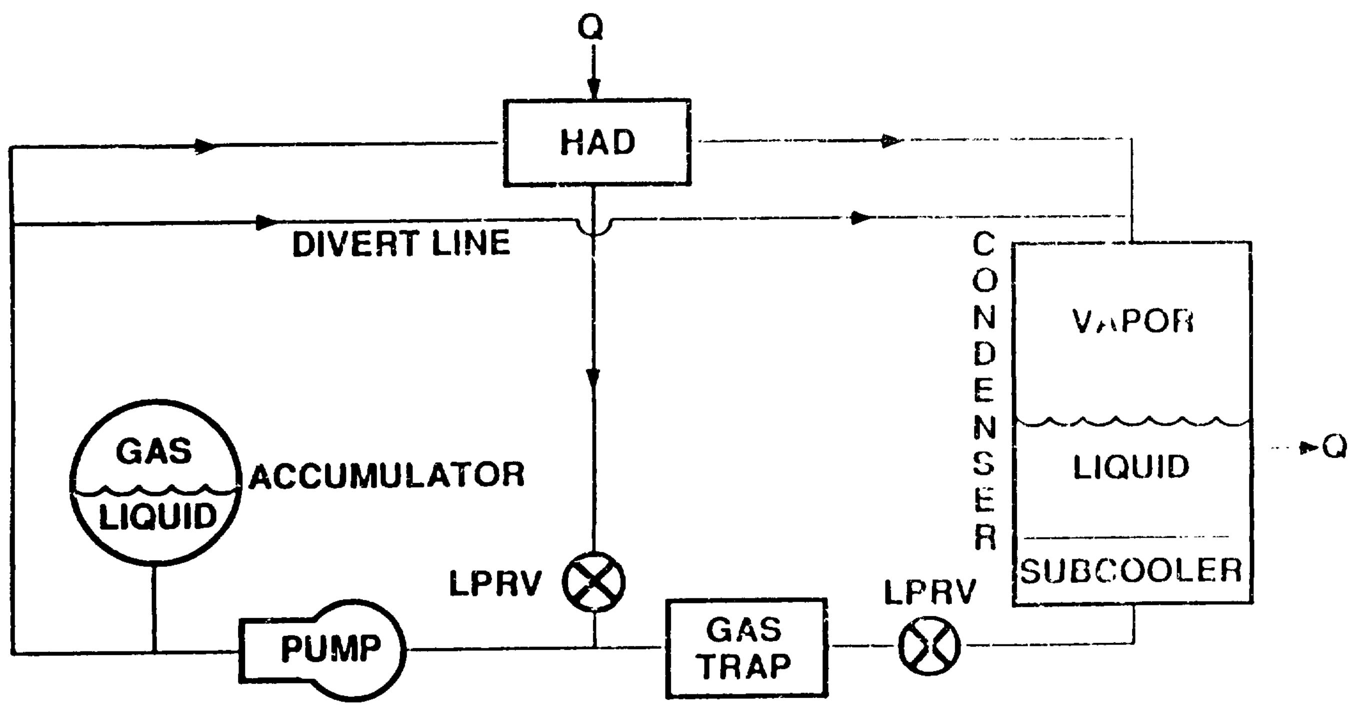
- 2 ACCUMULATORS
- 1 SUPPLY TANK
- 1 DUMP TANK
- 4 PUMPS
- 4 FILTERS
- 2 N2 TANKS
- 2 NCG TRAPS
- 8 CONTROL VALVES
- 60 NH3 ISOLATION VALVES
- 17 N2/WASTE GAS ISOLATION VALVES
- 4 N2 PRESSURE REGULATORS
- INTERCONNECT LINES
- POWER LINES
- SENSORS
- 48 NH3 QDS
- 10 N2/WASTE GAS QDS
- TBD CONDENSER MODULES

OTHER SYSTEMS

- 1 PDCA
- 1 RADIATOR FLUID COUPLING
- 2 MDMs
- METEOROID SHIELD
- INSULATION
- 17 FLUID INTERFACE LINES
- POWER/DATA INTERFACE CABLES
- 1 POWER CONDITIONING UNIT

- QD
- CONTROL VALVE
- ISOLATION VALVE
- NCG TRAP
- FILTER

LMSC SYSTEM SCHEMATIC



DEVELOPMENT ISSUES

Key Technical Challenges Heat Rejection	Approach to Challenges
■ High capacity heat pipe radiator	• Two technology options (GAC and LMSC) • Thermal test bed • KC-135 tests • STS-8 concept flight test (OAST) • STS-29 SHARE* technology flight test (Advanced Development) • STS-43 SHARE II* Development Flight Test (Prime)
■ On-orbit assembly	• EVA and RMS Ooptions • WETF evaluations • RMS ground test facility evaluations • STS-61 SRAD* verification flight test (Prime)

*SHARE - Station Heat Rejection Advanced Radiator Element
SHARE II - Station Heat Rejection Advanced Radiator Element
SRAD - Shuttle Radiator Assembly Demonstration

DEVELOPMENT ISSUES
(Continued)

Key Technical Challenges Heat Acquisition/Transport	Approach to Challenges
■ Two phase thermal bus	• Three technology options (Boeing, GAC, LMSC) • Thermal test bed • KC-135 tests • STS-61 TPITS verification flight test (Prime)
■ Rotary fluid coupler	• Three technology options (Boeing, LaRC, LMSC) • Thermal test bed
■ Leak detection, isolation, and repair	• Thermal test bed

THERMAL FLIGHT EXPERIMENTS

- **SHARE - Station Heat Rejection Advanced Radiator Element**
  - One 50 ft advanced development heat pipe radiator panel performance
  - STS-29 (3/89)
- **SHARE II - Station Heat Rejection Advanced Radiator Element**
  - Two 43 ft station development heat pipe radiator panels performance
  - STS-43 (1/91)
- **SRAD - Shuttle Radiator Assembly Demonstration**
  - Three heat pipe radiator panels assembled on-orbit by RMS and EVA
  - Thermal performance
  - Accepts heat from simulated or TPITS two-phase thermal bus
  - STS-61 (11/92), manifested with TPITS
- **TPITS - Two-Phase Integrated Thermal System**
  - 5 kW thermal bus performance
  - Reject heat to Orbiter payload heat exchanger or SRAD-erected radiators
  - STS-61 (11/92), manifested with SRAD

Thermal Control System

Invited Presentations

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N93-27844

TECHNOLOGY FOR SPACE STATION
EVOLUTION WORKSHOP

ADVANCED INTERFACE HEAT EXCHANGERS FOR THE SPACE STATION MAIN THERMAL BUS

NASA CONTRACTS: NAS 9–17810
NAS 9–17989
NAS 9–18167

JAVIER A. VALENZUELA

CREARE INC.
HANOVER, NH

Future evolution and growth of the Space Station will place increasing demands on the thermal management system by the addition of new payloads and from increased activity in the habitat modules. To meet this need, Creare is developing, under the sponsorship of NASA JSC, advanced evaporators, condensers, and single–phase heat exchangers for operation in micro gravity. The objective is to achieve a several–fold increase in the heat flux capability of these components, while operating at the same temperature difference as specified for the present interface heat exchangers. Two prototype interface heat exchangers are presently being developed: one to interface the main thermal bus to a payload two–phase ammonia bus, and the other, to interface with the crew module single–phase water loop. This presentation will review the results achieved to date in the development of these heat exchangers.

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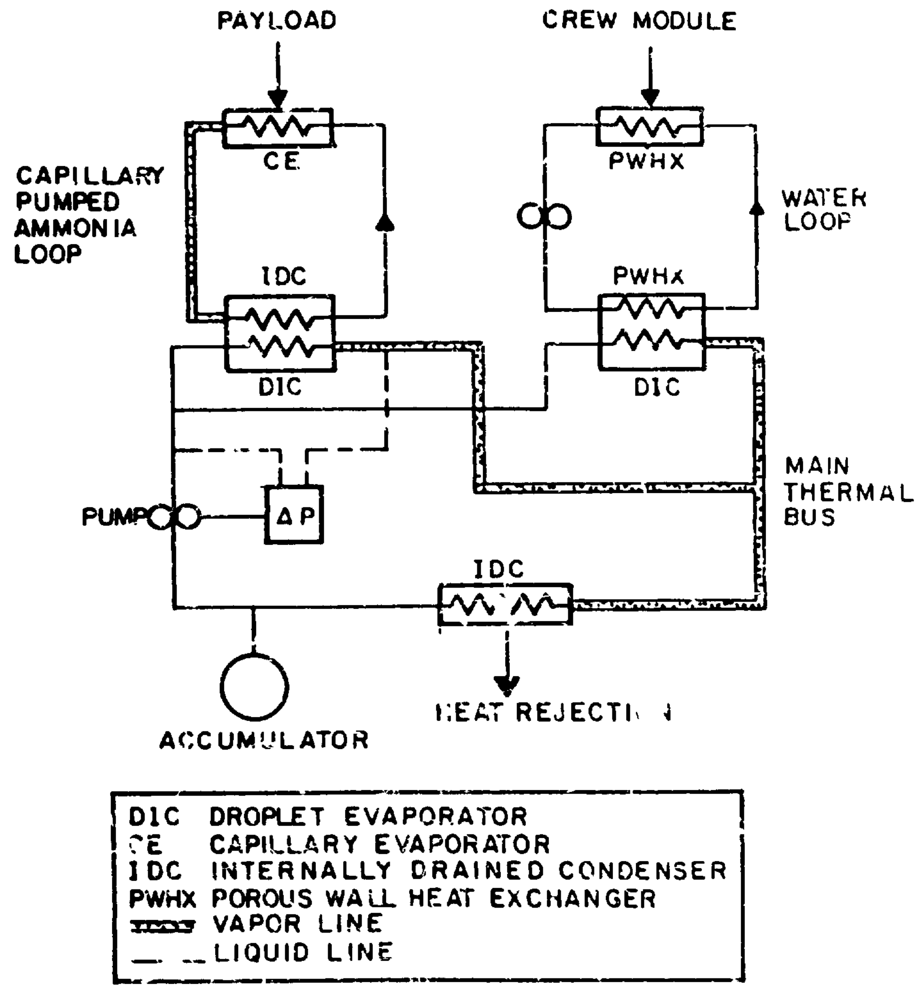
PROGRAM OVERVIEW



The objectives of this program are to develop advanced heat transfer techniques to allow a several–fold reduction in the size of interface heat exchangers for future space thermal management systems.

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PROGRAM OBJECTIVES

DEVELOP NEW HEAT TRANSFER TECHNIQUES

1. DROPLET IMPINGEMENT COOLING
2. INTERNALLY DRAINED CONDENSER
3. POROUS WALL HEAT EXCHANGER

PROGRAM GOAL

SEVERAL FOLD REDUCTION IN SIZE AND WEIGHT OF SPACE THERMAL MANAGEMENT COMPONENTS

The evaporator uses droplet impingement cooling (DIC) to achieve heat transfer coefficients in excess of 10 W/cm^2–°C. A piezoelectric transducer is used to eject an array of small diameter (100 micron) drops at high velocity (10 m/s). These drops impinge on the heat transfer surface and spread out forming a liquid film only a few microns thick. Because the film is so thin the temperature gradients at the wall are very large, and bubble nucleation is inhibited, even at large values of wall superheat. Heat is conducted through this thin film, and liquid evaporates at the surface of the film removing heat. Since there is no nucleate boiling, the film remains attached to the wall and there is no liquid carryover in the vapor stream. A simple temperature feedback loop regulates the droplet generation rate to maintain the wall at the desired temperature.

Droplet impingement cooling differs from spray cooling in three important respects. First, in DIC drop pattern is highly uniform as compared with the random distribution of drops in a spray. Second, in DIC the drop frequency is regulated so that a given set of drops evaporates completely prior to the arrival of the next set. Finally, in DIC all the liquid evaporates – single phase liquid enters the evaporator and only vapor leaves the evaporator.

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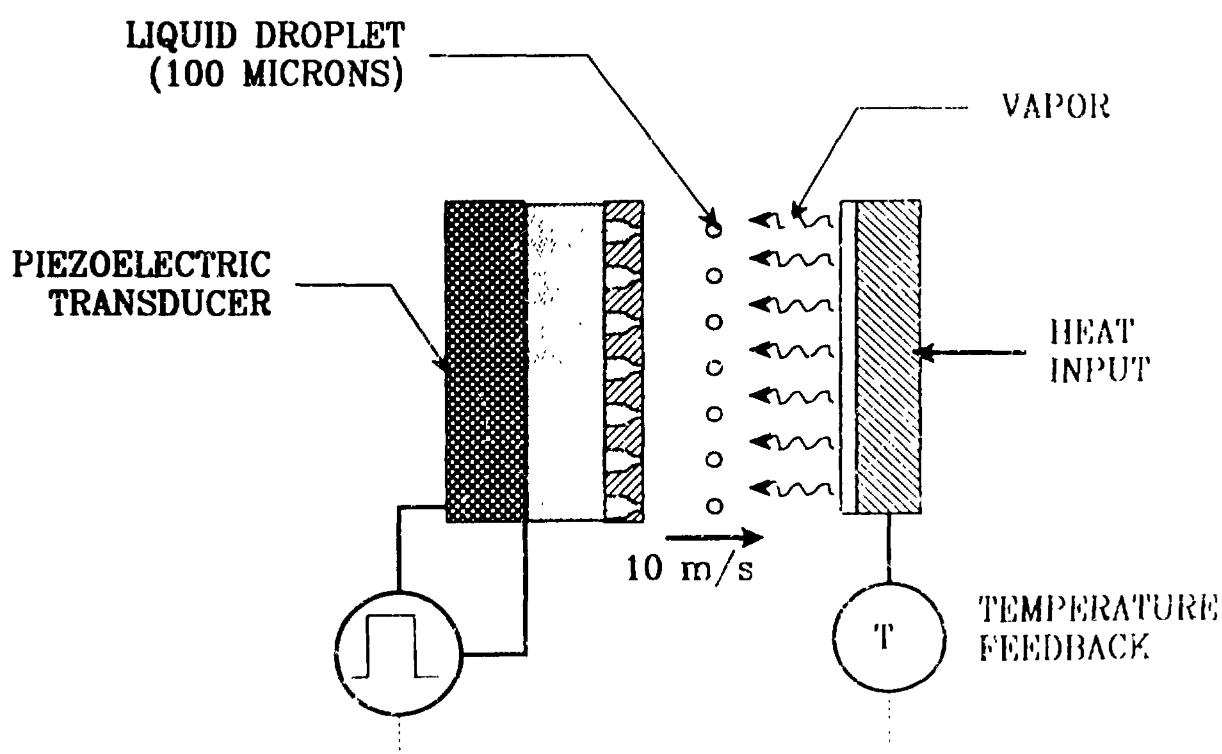
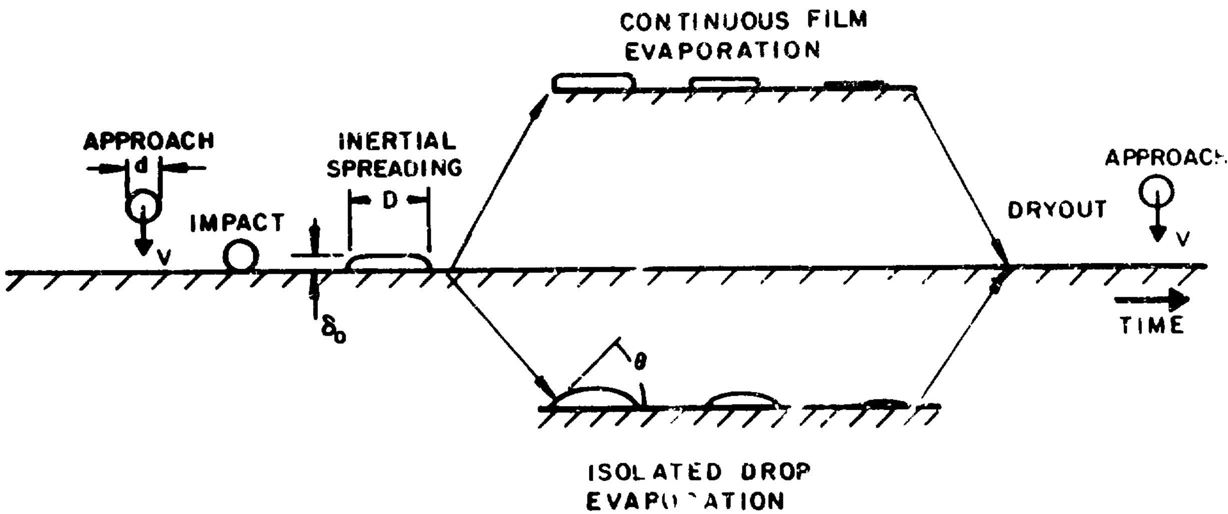
DROPLET IMPINGEMENT COOLING CONCEPT



There are two modes of droplet impingement cooling: film evaporation, and isolated drop evaporation. If the drop packing density is high enough, adjacent drops will merge upon impact forming a continuous film. If the drop packing density is low, they will evaporate as separate lens shaped drops.

The drop spreading time and the liquid thermal diffusion time are orders of magnitude shorter than the drop evaporation time. Hence, the DIC process can be modeled as quasi–steady state conduction through a progressively thinner liquid film or lens.

DIC CHARACTERISTIC DIMENSIONS AND TIME SCALES



DROP DIAMETER	$d \cong 100\ \mu m$
DROP VELOCITY	$V \cong 10$ ms
SPOT DIAMETER	$D \cong 500\ \mu m$
INITIAL SPOT THICKNESS	$\delta \cong 3\ \mu m$
DROP FLIGHT TIME	$\tau_v \cong 0.3$ m/s
SPOT FORMATION TIME	$\tau_f \cong 0.05$ m/s
SPOT THERMAL DIFFUSION TIME	$\tau_t \cong 0.04$ m/s
SPOT EVAPORATION TIME	$\tau_c \cong 10$ ms

There are four heat transfer regimes in DIC. For low surface superheats, bubble nucleation is inhibited by the steep temperature gradient in the film, and evaporation only takes place at the surface of the film. Beyond a critical superheat value, which depends on the initial film thickness, nucleate boiling is initiated. In nucleate boiling the bursting bubbles fling liquid away from the surface reducing the cooling capacity of the drops and leading to the critical heat flux (CHF) condition. The heat flux decreases with further increases in wall superheat. At even higher values of wall superheat the Leidenfrost condition is reached, where the droplets no longer contact the surface. Evaporation of the droplets as they approach the surface forms a vapor cushion which causes the drops to rebound. Only a small percentage of the drop volume is evaporated in this heat transfer regime.

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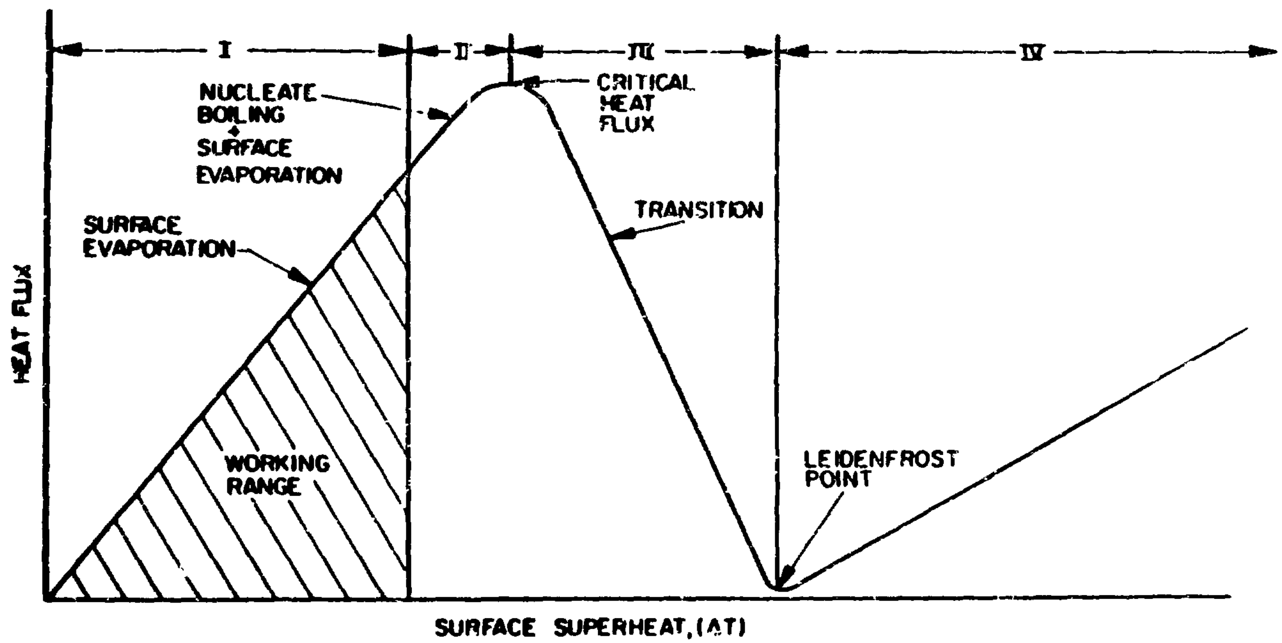
DIC HEAT TRANSFER REGIMES



Proof–of–concept experiments performed in water confirm the shape of the heat transfer regimes curve and demonstrate that very high heat fluxes are possible in DIC. The measured CHF was 330 W/cm^2, more than twice CHF for pool boiling. The heat transfer coefficient is also very high, about 9 W/cm^2–°C.

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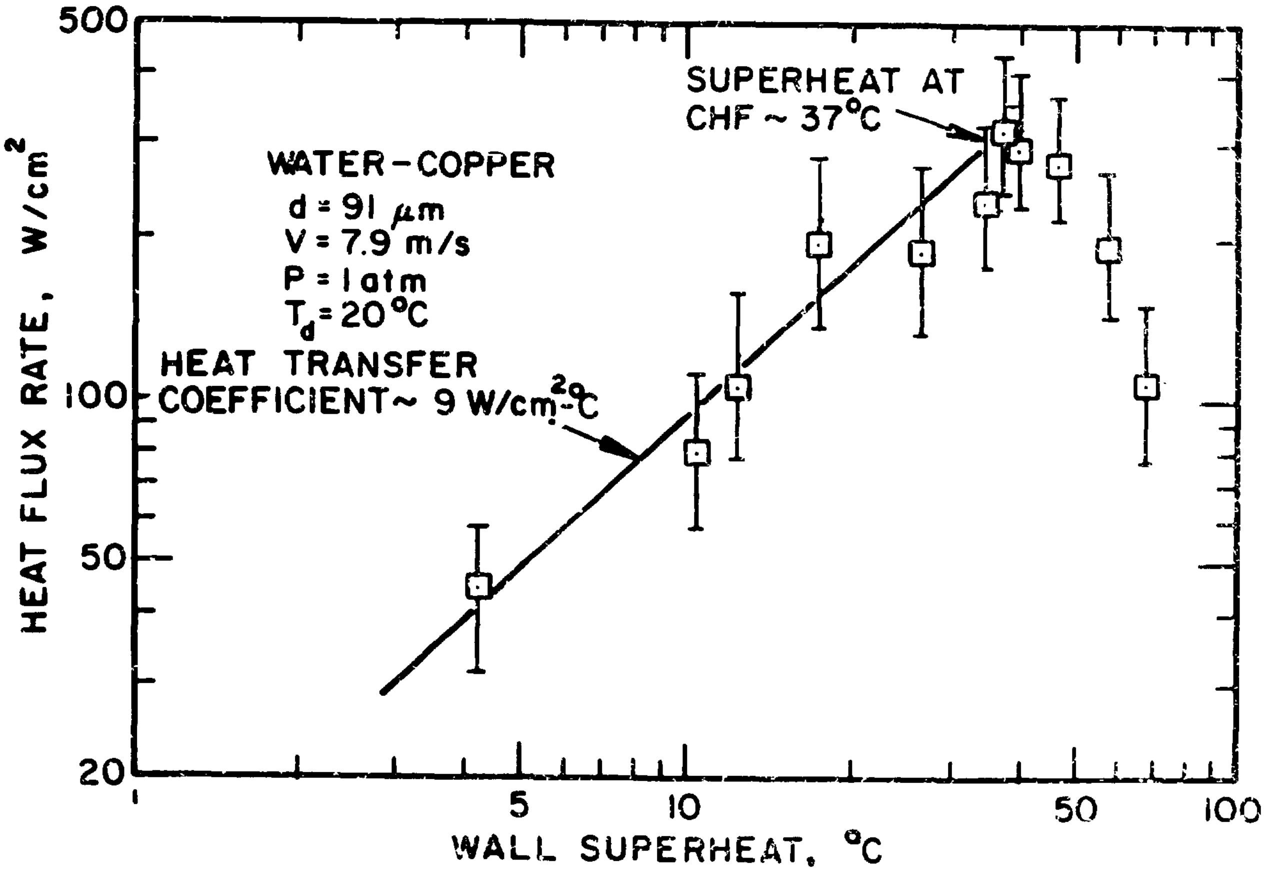
DIC DATA FOR WATER AT 1 ATM



The DIC heat transfer coefficient depends primarily on the initial liquid film thickness (film thickness immediately following drop impact). For conditions of interest, the initial film thickness will range between 5 and 10 microns. Heat transfer coefficients in ammonia can be as high as 15 $W/cm^2{}^\circ C$.

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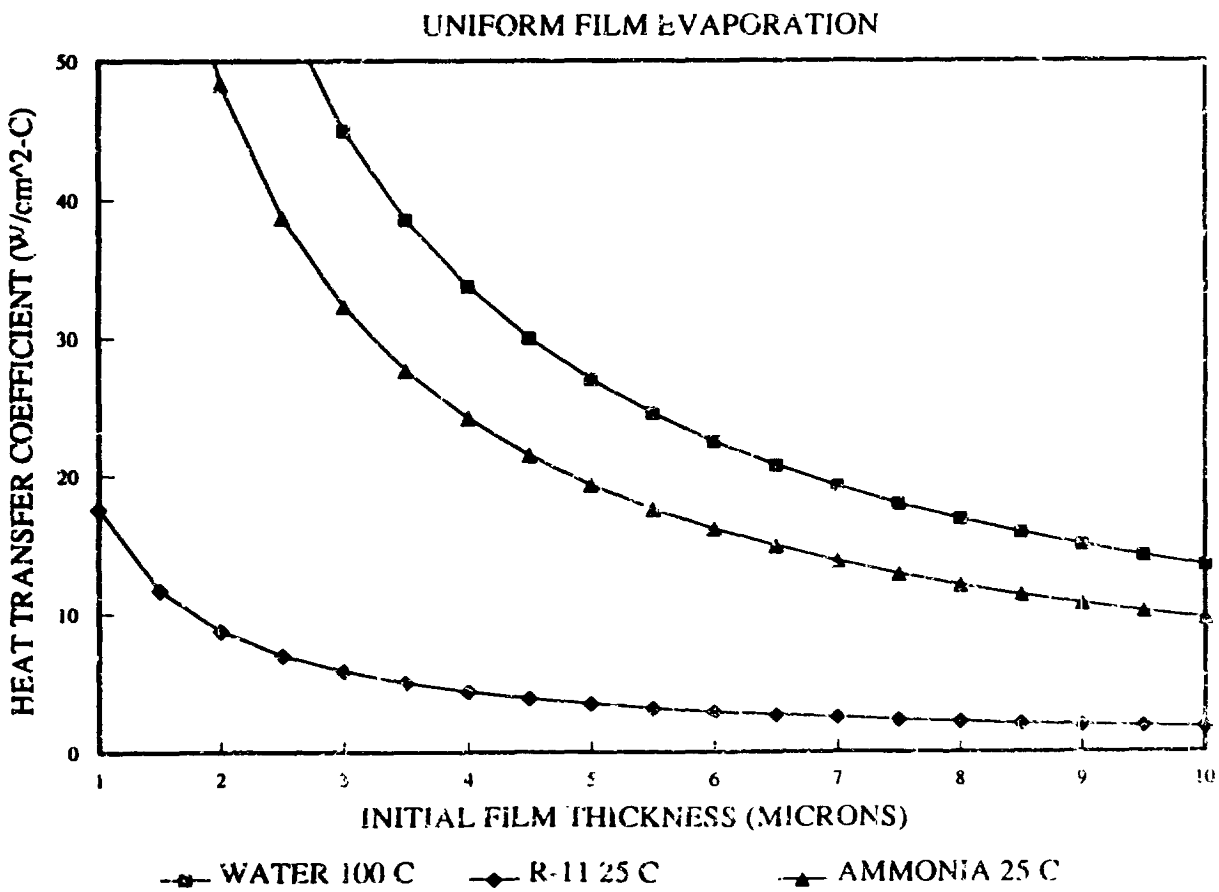
PREDICTED DIC HEAT TRANSFER COEFFICIENT



The condenser uses Gregorig fins in conjunction with an internal drainage network to achieve heat transfer coefficients comparable to those of the droplet evaporator. The main innovation in this condenser is that the condensate is drained through ducts embedded in the wall itself. The condensate only travels a short distance (less than a millimeter) over the surface of the condenser before being removed from the surface. Hence, the entire capillary pressure gradient available can be used to drive the condensate over this short distance. The resulting liquid velocities are high, leading to condensate films only a few microns thick.

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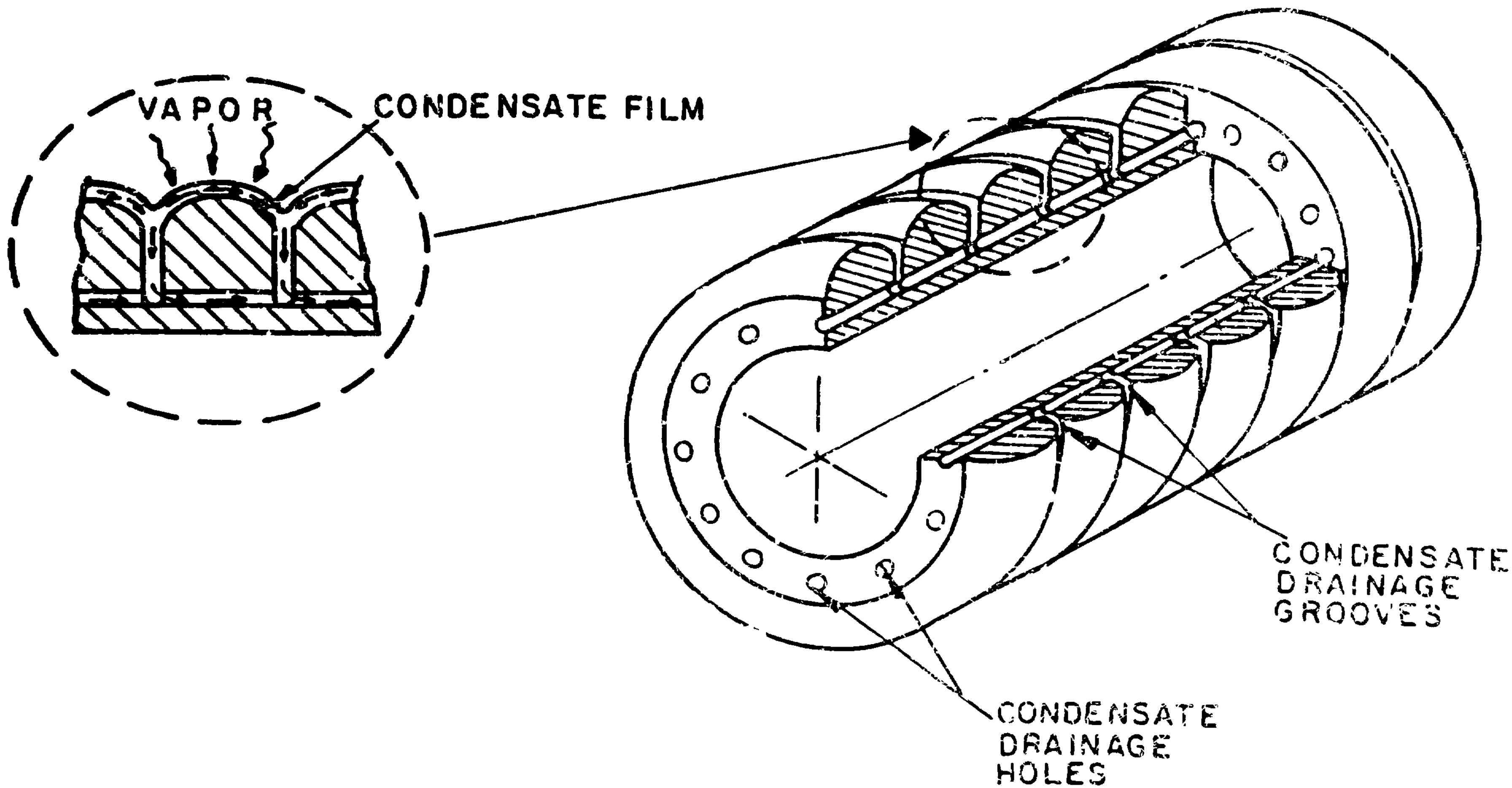
INTERNALLY DRAINED CONDENSER CONCEPT



By optimizing the shape of the fins very high capillary pressure gradients can be obtained. For a 1 mm wide fin, the capillary pressure gradient can be 20 times higher than gravitational pressure gradient in 1g. The high pressure gradient results in extremely thin condensate films and hence high heat transfer coefficients.

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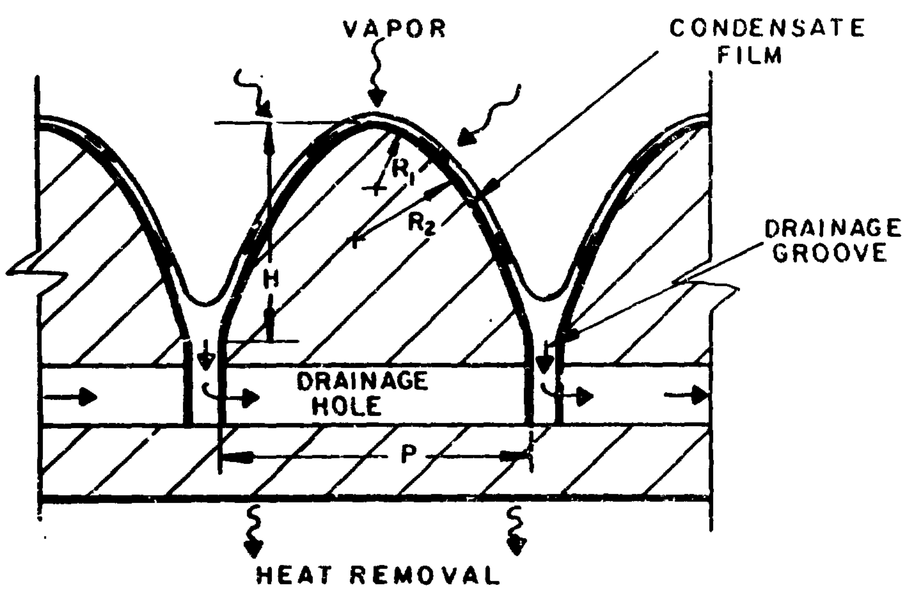
IDC OPERATION



Capillary Drainage

$$\left[\frac{dp}{ds}\right]_c = \sigma \frac{d}{ds}\left|\frac{1}{R}\right| \cong \frac{3\sigma}{P^2}$$

Gravitational Drainage

$$\left[\frac{dp}{ds}\right]_g = \frac{H\rho g}{S} \cong 0.6\,\rho g$$

Ammonia, P = 1 mm

$$\frac{\left[\frac{dp}{ds}\right]_c}{\left[\frac{dp}{ds}\right]_g} = 20$$

The heat transfer coefficient in the internally drained condenser (IDC) depends on the suction level applied to the drainage ducts. At suction levels below the drainage groove capillary pressure, the fins are partially flooded and the heat transfer coefficient varies from close to zero to a maximum value. For suction levels between one and four times the capillary pressure of the drainage groove, the heat transfer coefficient remains constants. At higher suction levels, vapor is pulled into the drainage ducts. By controlling the suction level, the IDC can be used as a variable conductance element. Because the grooves are so small, very little liquid is required to vary the heat transfer coefficient over a wide range. This would reduce the size of the accumulator required for temperature control of the thermal bus.

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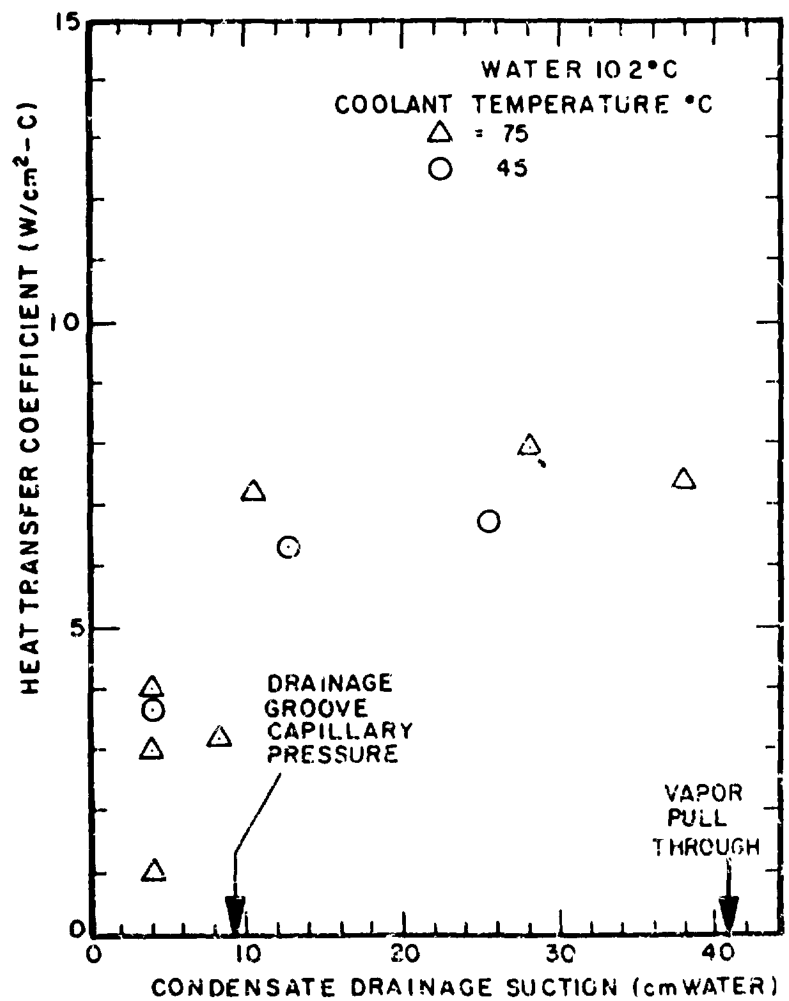
EFFECT OF SUCTION LEVEL ON IDC PERFORMANCE



The heat transfer coefficient in the IDC is very high, about eight times higher than that of a smooth tube operating at equal heat flux. The IDC contoured fins provides about twice as much enhancement as rectangular fins in a 1 G environment. The performance of the IDC can be well predicted using analytical models.

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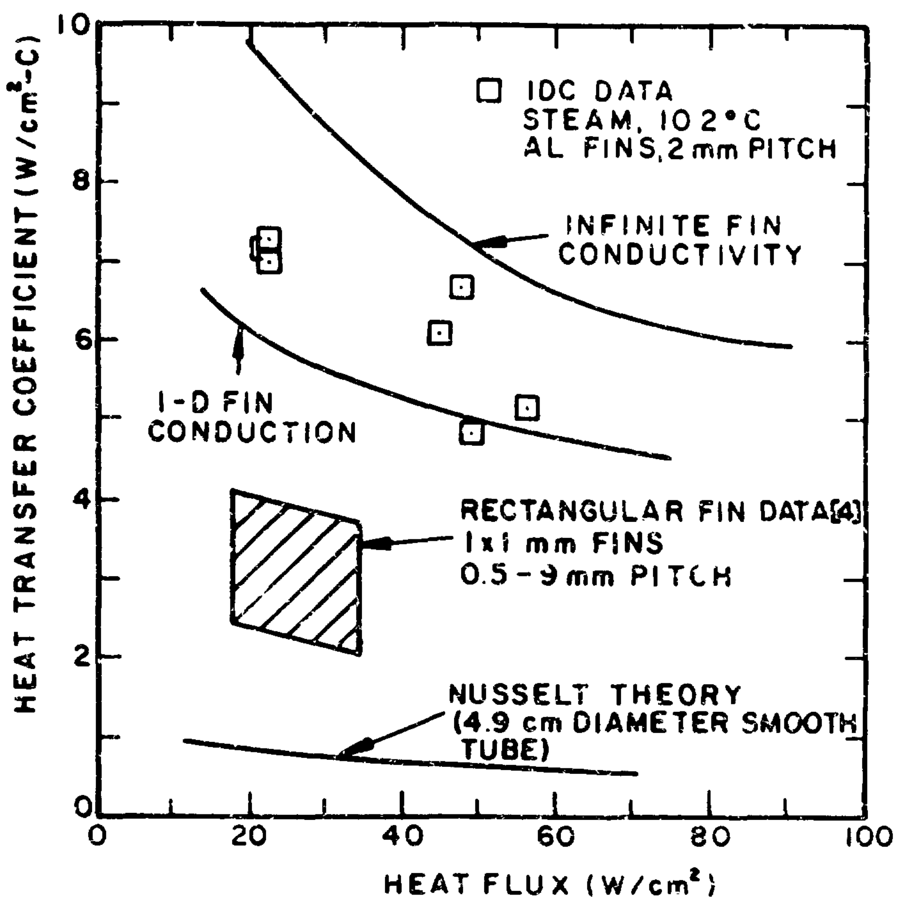
IDC MEASURED HEAT TRANSFER COEFFICIENT



High heat transfer coefficients can also be achieved in ammonia. A surface suocooling of only 1°C will result in a heat flux of about 9 W/cm^2–°C.

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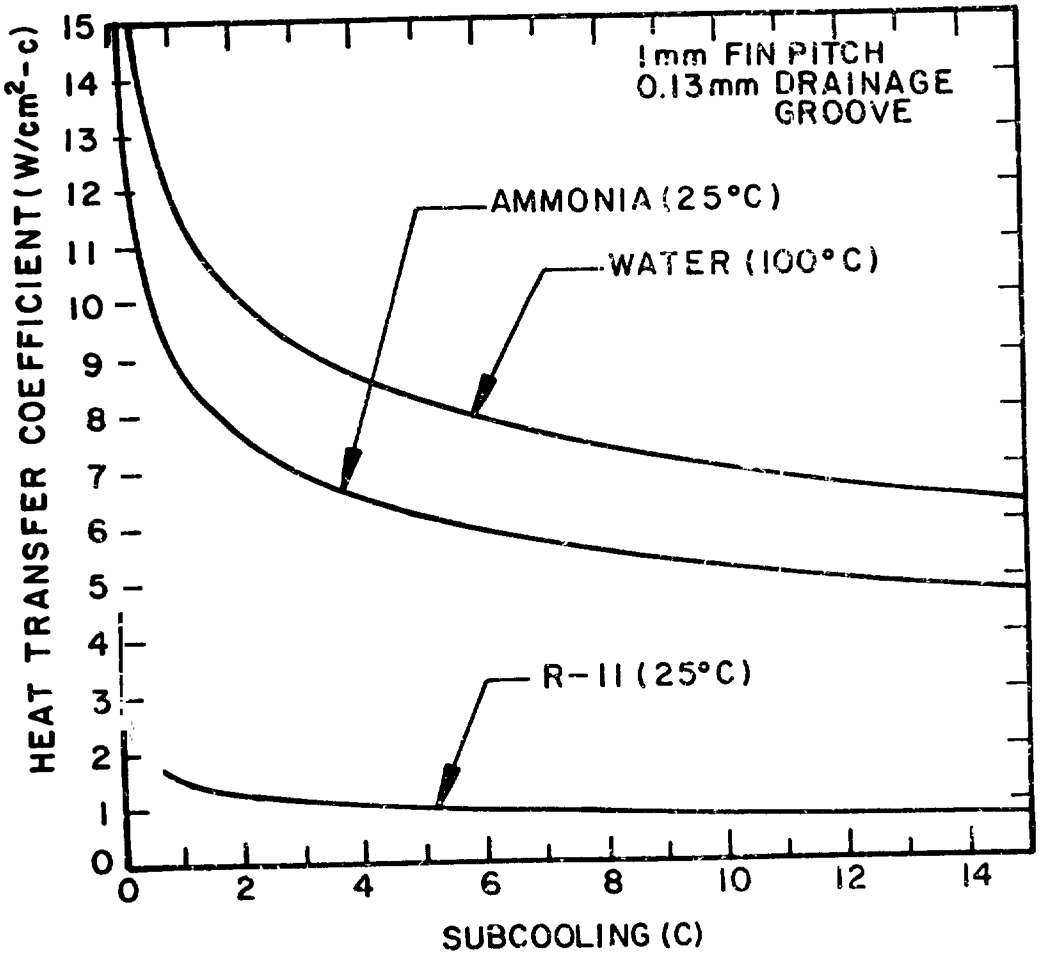
PREDICTED CONDENSATION HEAT TRANSFER COEFFICIENT AS A FUNCTION OF SUBCOOLING



The single–phase heat exchanger is perhaps the most challenging component from a performance standpoint. Heat transfer coefficients in conventional single–phase heat exchangers are so much lower than those in two–phase systems that the water side drives the size and performance of the heat exchanger. Creare has developed[1] a new single–phase heat exchanger concept which can achieve heat fluxes comparable to those of the droplet evaporator with high effectiveness and low pressure drop.

The heat exchanger consists of a layer of closely spaced fins in good thermal contact with the heat transfer surface. The fins form a "porous layer" though which the fluid flows. The fin spacing is small, typically 0.1 mm or less. The fluid is therefore in excellent thermal communication with the fins. The fluid leaves the heat exchanger through an array of small diameter ducts located at the interface between the "porous layer" and the heat transfer surface.

The main difference between the porous wall heat exchanger concept and conventional finned plate heat exchangers is the direction of the flow. In the PWHX the fluid flows in a direction normal to the heat transfer surface, whereas in a conventional heat exchanger, the fluid flows parallel to the surface. Normal flow aligns the directions of the temperature gradients in the fins and the fluid and results in high effectiveness even at high heat fluxes. The fins are very short and, therefore, pressure drops in the PWHX are quite small.

[1] Patent pending.

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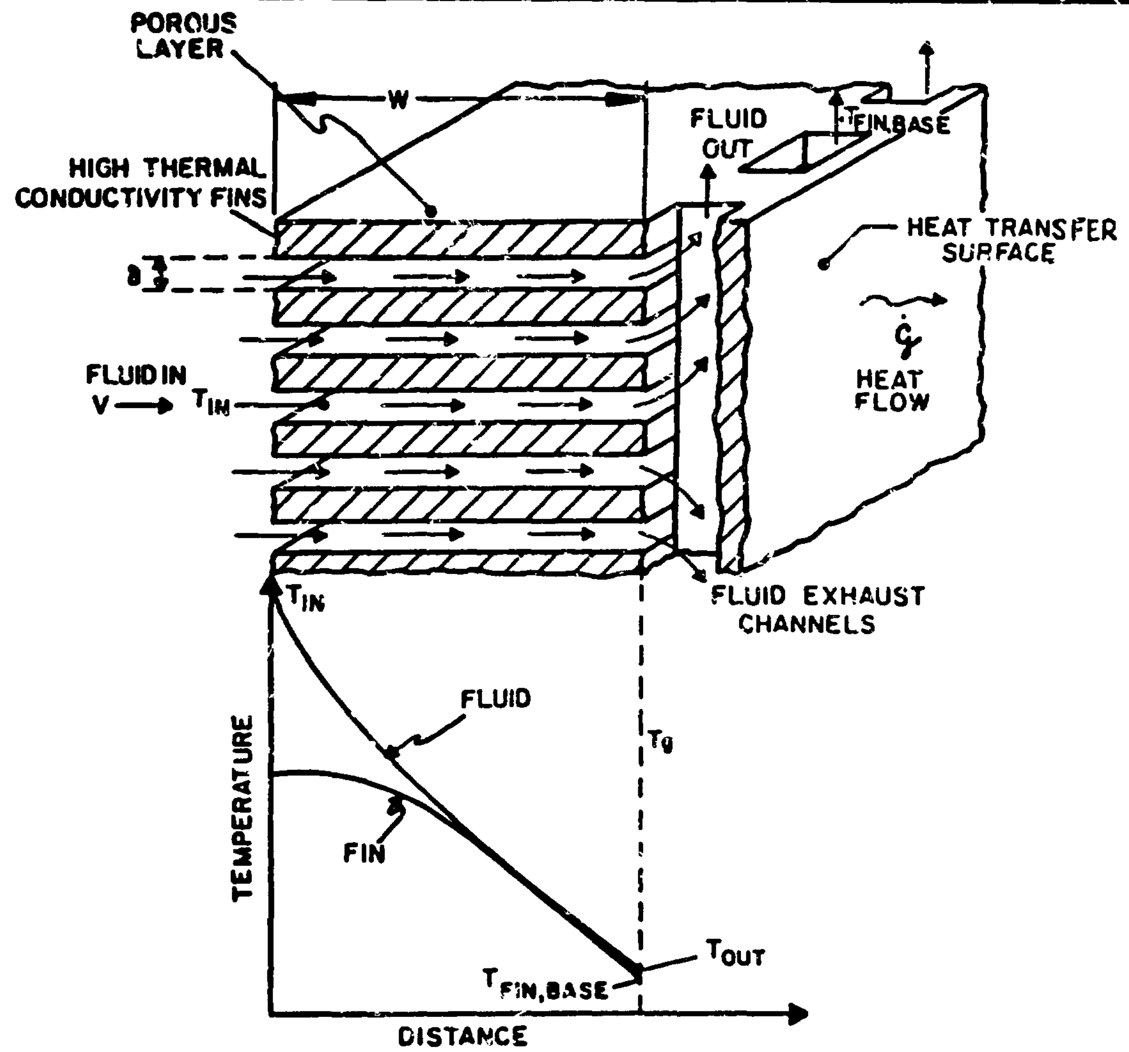
POROUS WALL HEAT EXCHANGER CONCEPT
PWHX



Proof–of–concept experiments performed in water achieved heat fluxes in excess of 60 W/cm^2–C with a pressure drop of only 250 Pa (0.04 psi).

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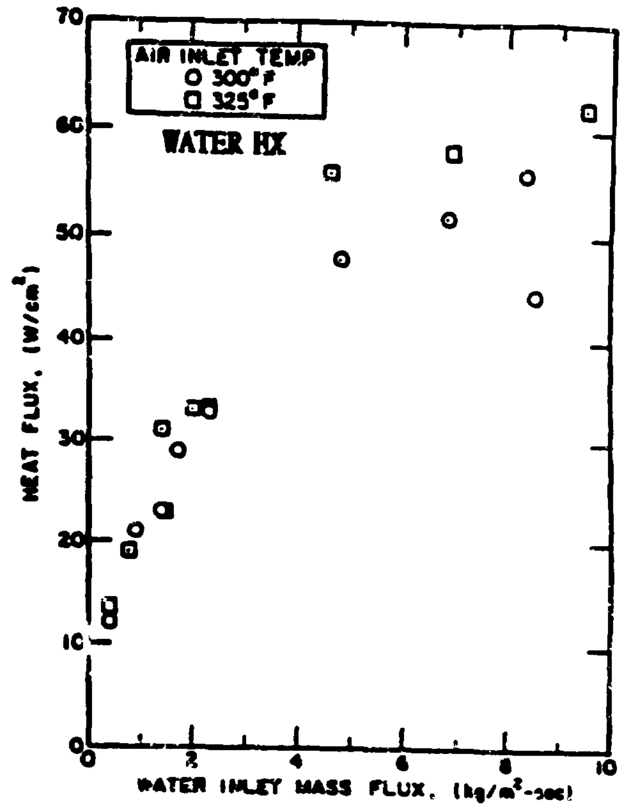
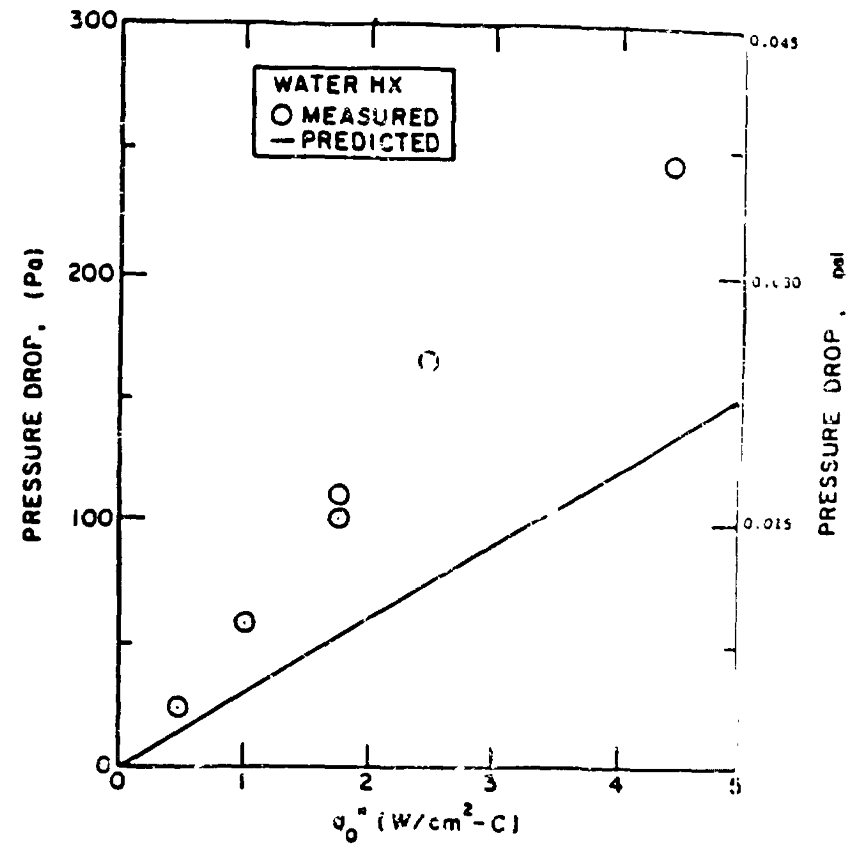
MEASURED HEAT FLUX AND PRESSURE DROP





The PWHX heat transfer coefficients are extremely high for a single phase heat exchanger. At a heat flux of 60 W/cm^2 the heat transfer coefficient was 4 W/cm^2—°C. The effectiveness was also high, about 70%. The heat transfer coefficient and effectiveness are lower than predicted because of flow maldistribution resulting from uneven fin spacing. Later experiments performed in air and helium have shown good agreement with the analytical models.

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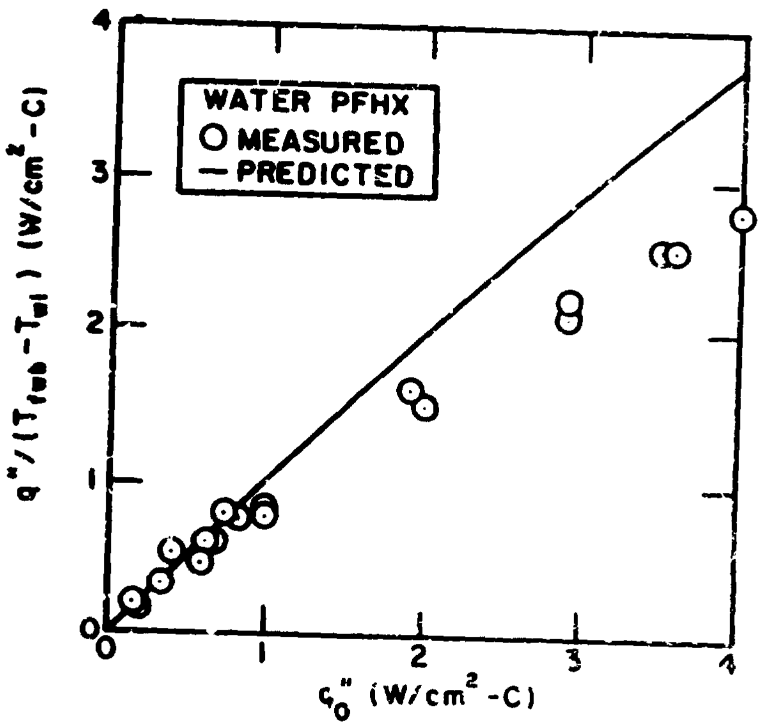
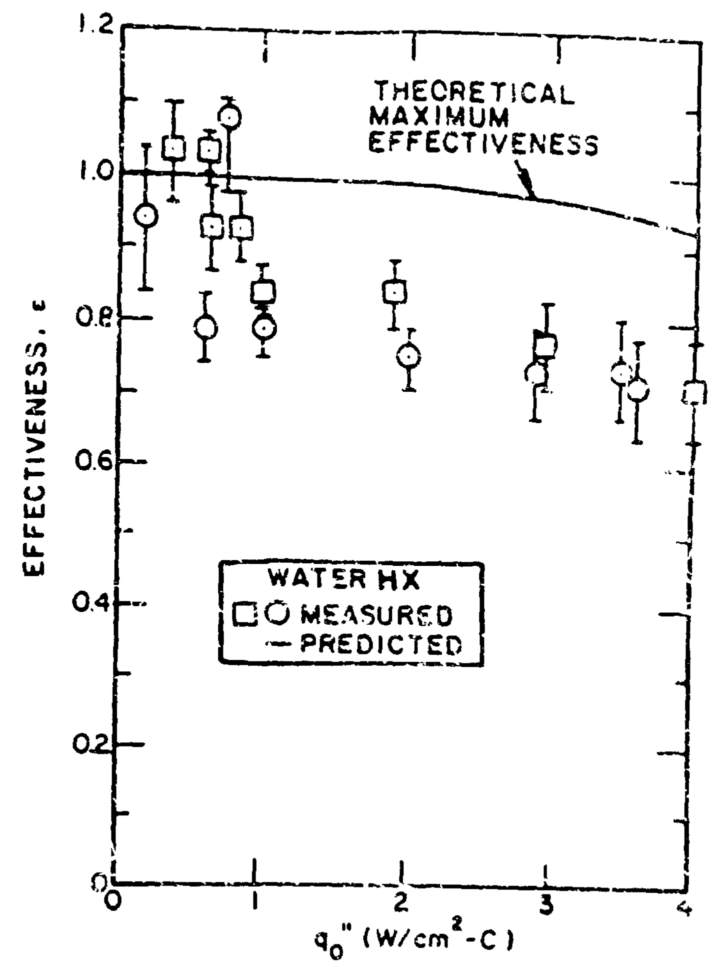
MEASURED HEAT TRANSFER COEFFICIENT AND EFFECTIVENESS





The PWHX performance depends strongly on the fin spacing. Smaller fin spacing leads to higher heat transfer coefficients and higher effectiveness. For a fin spacing of 0.05 mm, heat transfer coefficients of 20 W/cm^2–°C can be achieved with effectiveness in excess of 80%.

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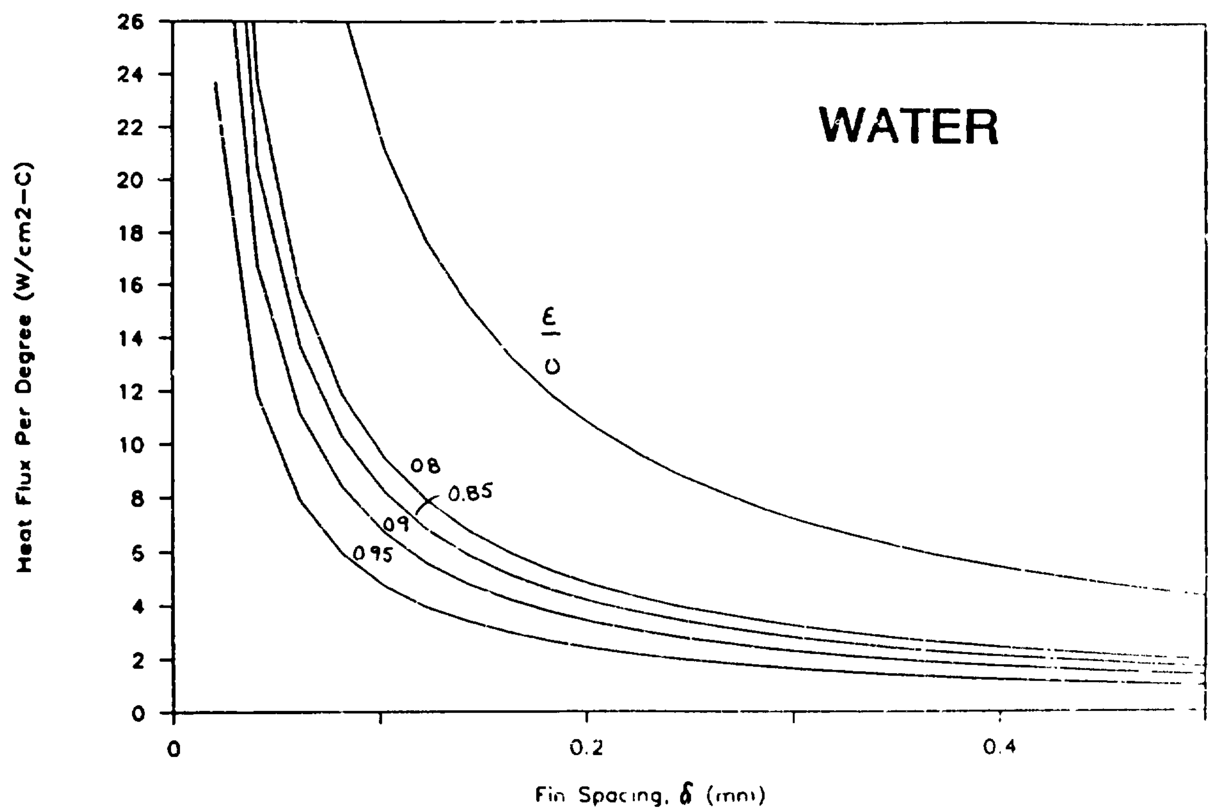
PREDICTED PWHX HEAT TRANSFER COEFFICIENT



The PWHX pressure drops are very small, typically less than a tenth of a psi.

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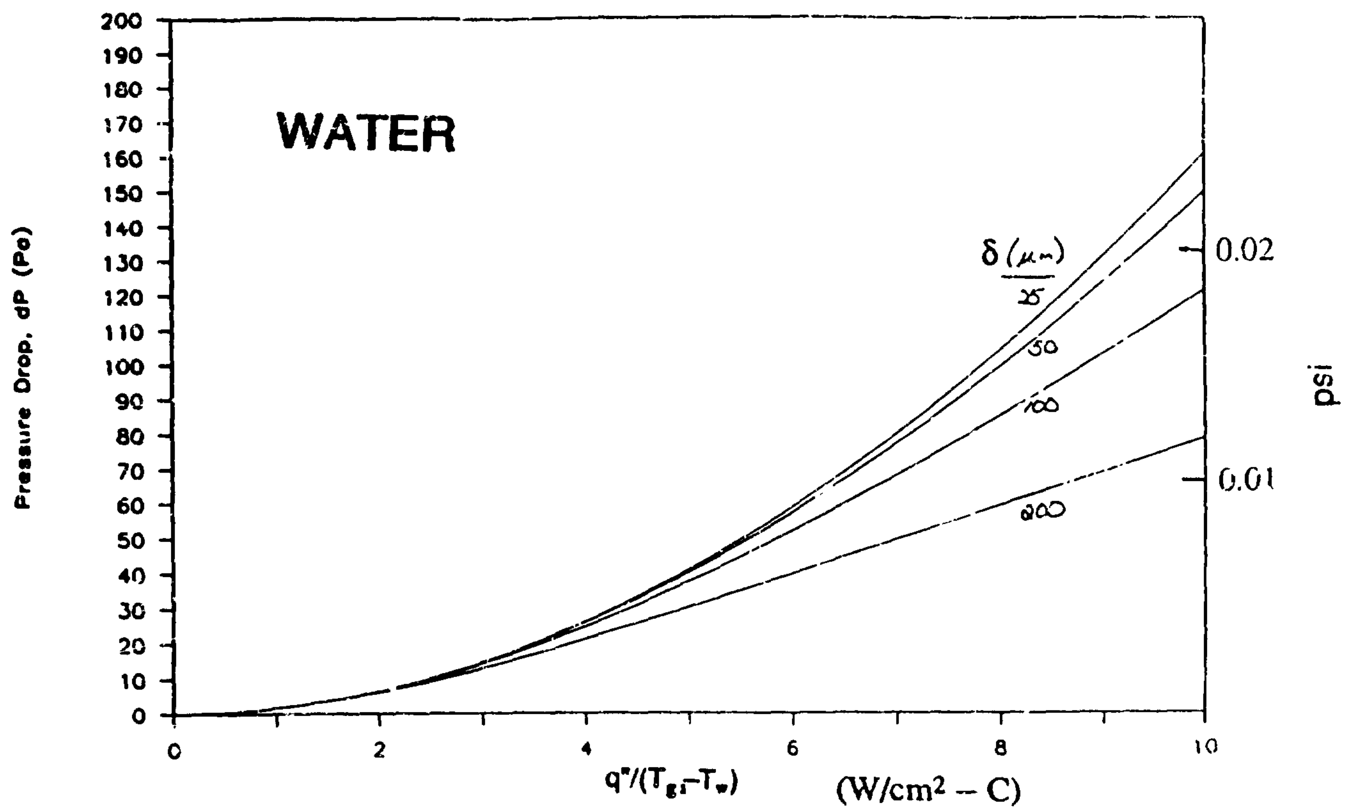
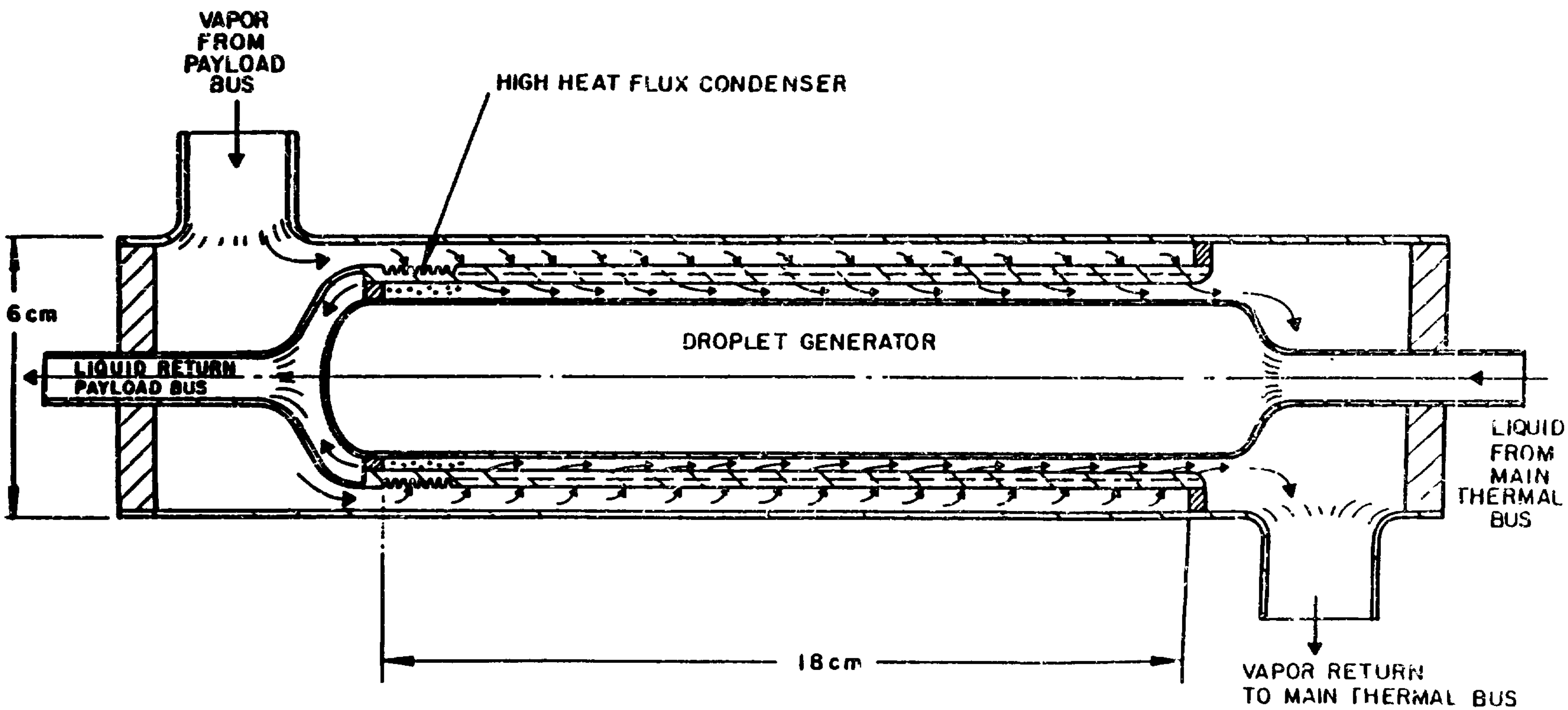
PREDICTED POROUS LAYER PRESSURE DROP



We are presently developing a payload interface heat exchanger which combines droplet impingement cooling on the evaporator side and the internally drained condenser on the condenser side. The heat exchanger will have a nominal capacity of 2 kW with an overall temperature difference of 5 °C or less.

CONCEPTUAL DESIGN OF PAYLOAD CTB–IF–HX



We are also developing a habitat interface heat exchanger which combines droplet impingement cooling on the ammonia side with the PWHX on the water side. The heat exchanger will also have a nominal capacity of 2 kW, an overall effectiveness of 73%, and a water side pressure drop of 0.1 psi.

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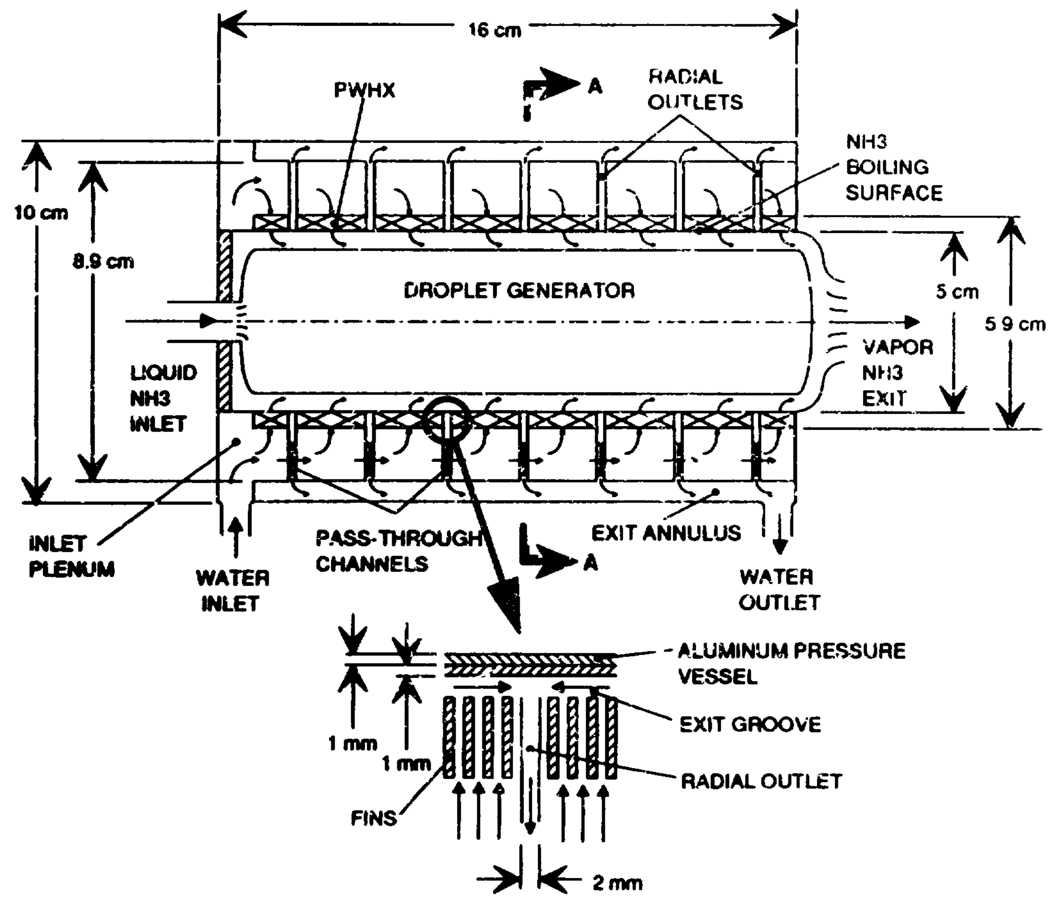
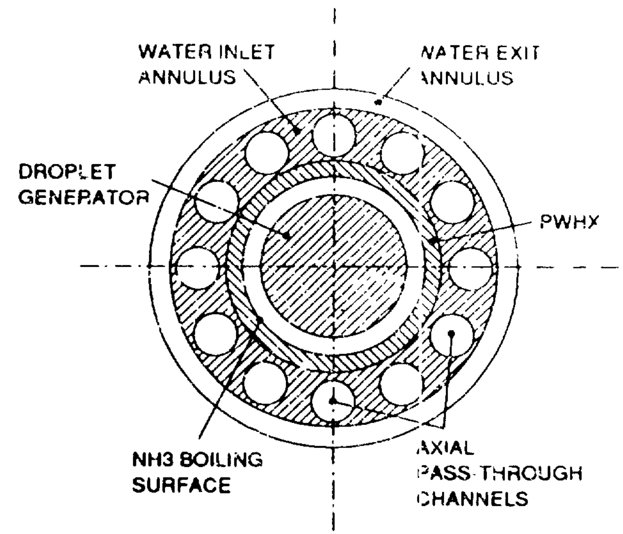
CONCEPTUAL DESIGN OF HABITAT CTB–IF–HX





SECTION A - A

The performance goals for these heat exchanger breadboards represent a several fold increase in the heat flux of present interface heat exchangers.

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PERFORMANCE GOALS

1. PAYLOAD CTB–IF–HX
   - h_{evap} = 10 W/cm^2–°C
   - h_{cond} = 10 W/cm^2–°C
   - q" = 10 W/cm^2

2. HABITAT CTB–IF–HX
   - h_{evap} = 10 W/cm^2–°C
   - h_{water} = 2 W/cm^2–°C
   - q" = 10 W/cm^2
   - EFFEC = 73%
   - ΔP_{water} = 150 Pa (0.1 psi)

The technology development issues in this program involve a combination of heat transfer modeling and optimization, coupled with the development of suitable fabrication techniques. All three heat transfer concepts require flow passages with small dimensions and extremely tight tolerances.

Creare

TECHNOLOGY DEVELOPMENT ISSUES

1. DROPLET EVAPORATOR
   - 1.1 DROPLET IMPINGEMENT HEAT TRANSFER
   - 1.2 MULTIORIFICE DROPLET GENERATOR
     - Nozzle Drilling
     - Piezoelectric Transducer Design

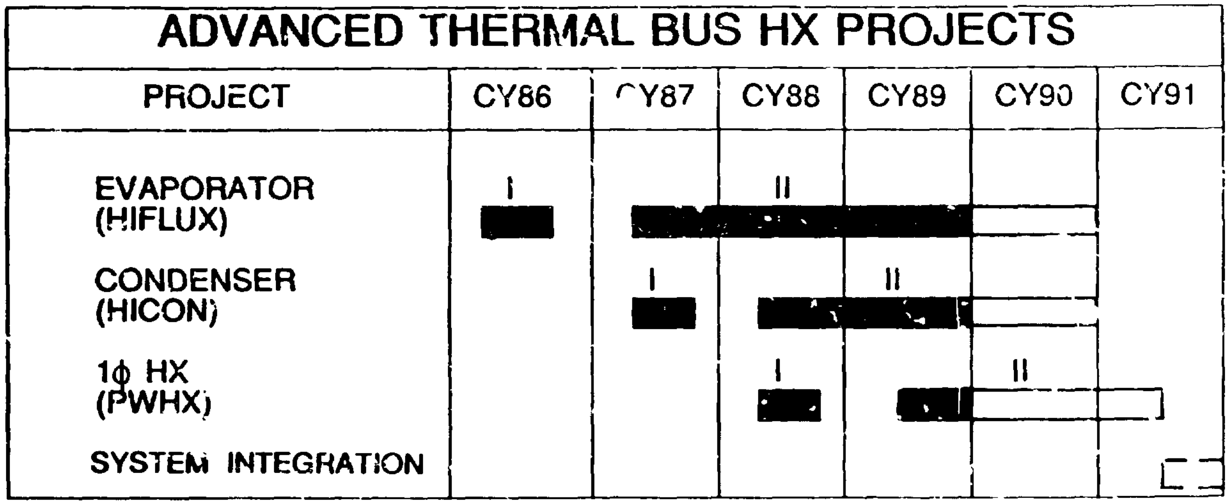
2. INTERNALLY DRAINED CONDENSER
   - 2.1 SURFACE SHAPE OPTIMIZATION
   - 2.2 FABRICATION TECHNIQUES
     - Surface Shape
     - Drainage Grooves
     - Drainage Ducts

3. POROUS WALL HEAT EXCHANGER
   - 3.1 HEAT TRANSFER AND PRESSURE DROP MODELS
   - 3.2 FABRICATION TECHNIQUES
     - Fins
     - Cu/Al Bonding
     - Flow Ducts

We have completed the design work for the evaporator and condenser. We will be testing the condenser and evaporator by themselves by mid 1990, and combined into an interface heat exchanger by the end of the year. The PWHX heat exchanger will be tested as a separate component in the second half of 1990, and integrated with the evaporator in early 1991 The next step in the development of this technology would be to integrate these components into a thermal bus.

Creare

PROGRAM SCHEDULE



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SPACE STATION FREEDOM
CENTRAL THERMAL CONTROL SYSTEM EVOLUTION

NASA - JOHNSON SPACE CENTER
Crew and Thermal Systems Division
Johnson Space Center

Eric Olsson
Lockheed Engineering and Science Company
Houston, Texas

For Presentation to the Space Station Technology Workshop
Dallas, TX - January 1990

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OBJECTIVE

IDENTIFY PRINCIPAL HOOKS AND SCARS FOR SSF TCS GROWTH

TYPES OF GROWTH

- RESOURCE GROWTH - PHYSICAL EXPANSION
- TECHNOLOGY GROWTH - HARDWARE OBSOLESCENCE AND INSERTION

GROWTH PERSPECTIVE

- SPACE STATION EVOLUTION DEFINITION - NASA LaRC
  - R & D Node - Technology/Commercial Mission
  - Transportation - Exploration Mission
- STATE OF THE TCS BASELINE
  - CTB Selection, 1ø/2ø Requirement, BMR's, etc ...
  - Program Rephasing in Late 1989 --> NO GROWTH

AGENDA

- REVIEW GROWTH REQUIREMENTS AND BASIC FEATURES OF R & D AND TRANSPORTATION NODES
- IDENTIFY THE PRINCIPAL CTCS HOOKS AND SCARS AT ASSEMBLY COMPLETE TO ACCOMMODATE GROWTH
- DESCRIBE THE GENERAL PROVISIONS FOR GROWTH AND IDENTIFY PERTINENT DESIGN ISSUES
- CONCLUSIONS

Lockheed Engineering & Sciences Company	SSF EVOLUTION TECHNOLOGY WORKSHOP	NASA/JSC - CREW AND THERMAL BY: ERIC OLSSON — DATE: JAN/90

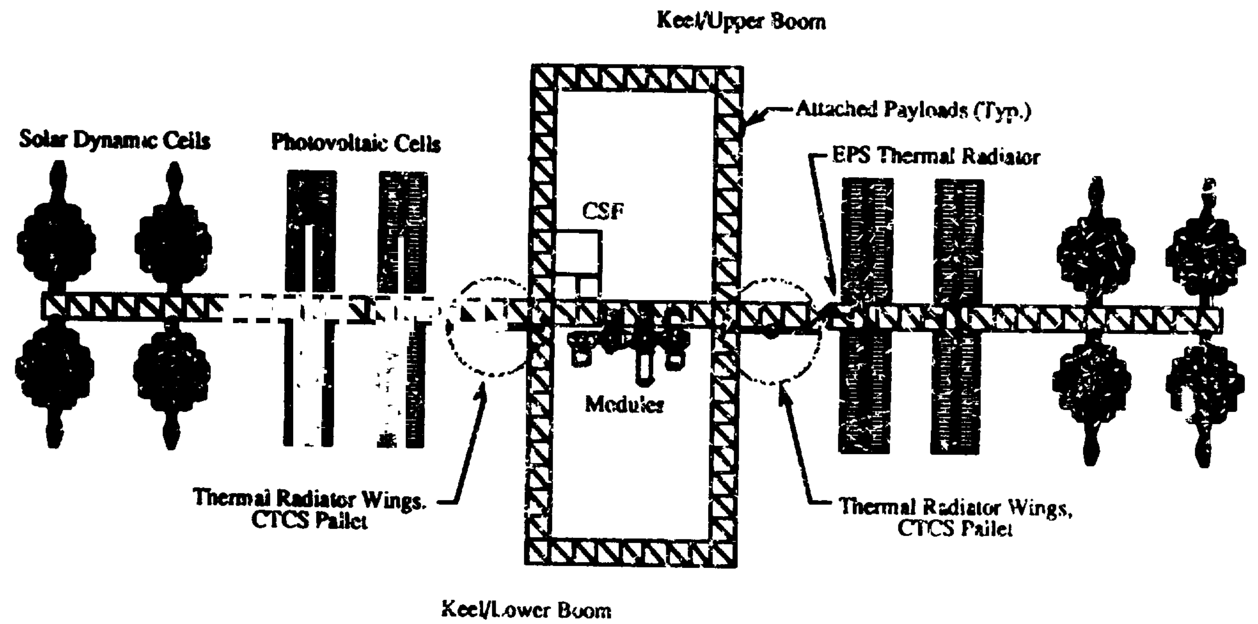
REQUIREMENTS FOR GROWTH

TCS REQUIREMENT	APPLICATION
HEAT REJECTION CAPABILITY	75 kW (82.2 kW) → 300 kW (325) or 181kW (200)
ON ORBIT RECONFIGURATION	VARIABLE TEMPERATURE LEVEL, HEAT LOAD
MODULARITY	SPACE ERECTABLE, REPLACEABLE
SAFETY	95% MINIMUM OPERATIONAL CAPABILITY
LEAK DETECTION	5% PER YR (PER LOOP) MAX LEAKAGE
QUIESCENT OPERATION	10% OF FULL LOAD
REDUNDANCY	TWO FAULT TOLERANCE
ISOTHERMALITY	±2.0°C
MONITOR & CONTROL	MINIMUM CREW INVOLVEMENT
TECHNOLOGY ACCOMMODATION	NO SYSTEM INTERUPTION

RESEARCH & DEVELOPMENT NODE

RESOURCES:

POWER	300 kW
THERMAL	325 kW
CREW	18
MODULES	3 Hab, 3 Lab, 2 Intn'l, 8 Nodes, 3 Pocket Lab, 2 Airlocks, 1 Logistics
SERVICING	CSF
APAE	5 Transverse Boom, 13 Dual Keel
STRUCTURE	17-A-15-A-17; Keel/Boom 10 x 9 Bays

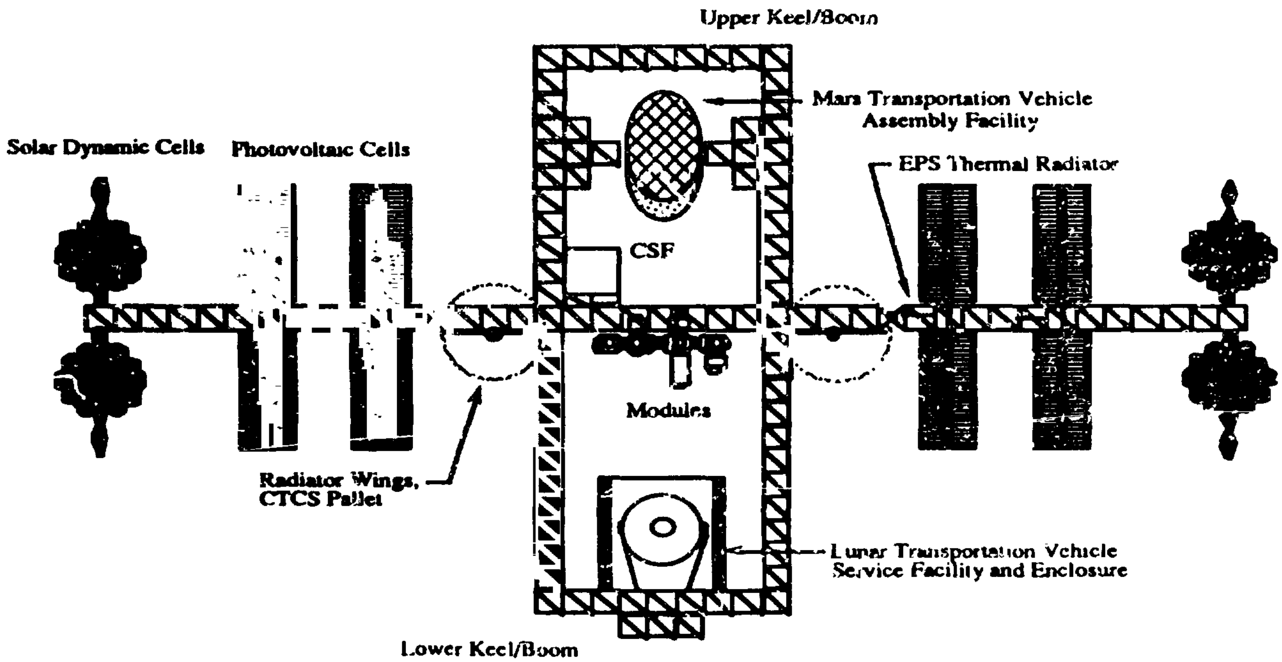


Lockheed Engineering & Sciences Company | SSF EVOLUTION TECHNOLOGY WORKSHOP | NASA/JSC - CREW AND THERMAL | BY: ERIC OLSSON | DATE: JAN/90

TRANSPORTATION NODE

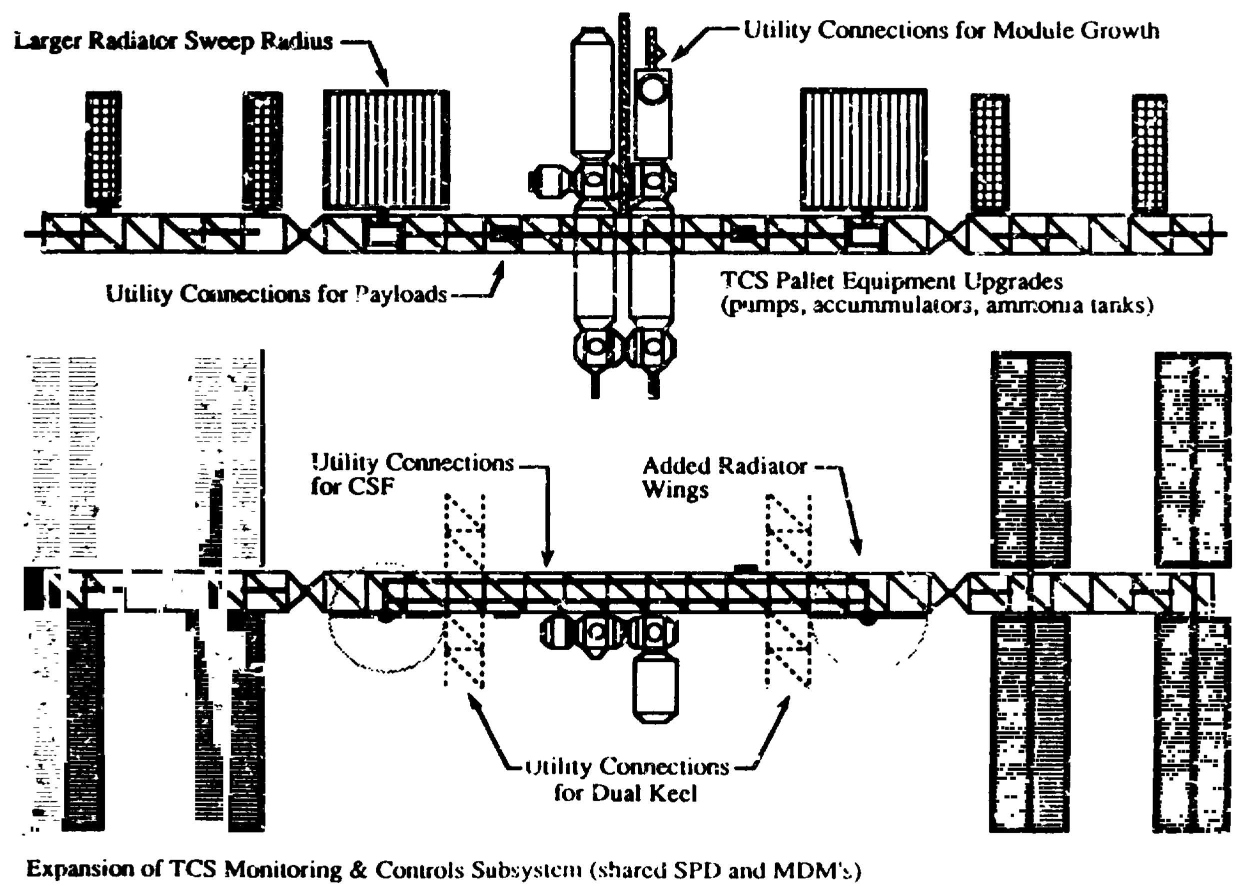
RESOURCES:

POWER	181 kW
THERMAL	200 kW
CREW	16 + 9 Transient
MODULES	3 Hab, 1 Lab, 2 Intn'l, 8 Nodes, 1 Pocket Lab, 2 Airlocks, 1 Logistics
SERVICING	CSF, LTV (+ Enclosure), MTV
APAE	8 (Location TBD)
STRUCTURE	[illegible]-A-12; Lower Keel/Boom 12 x 9, Upper Keel/Boom 11 x 9 Bays

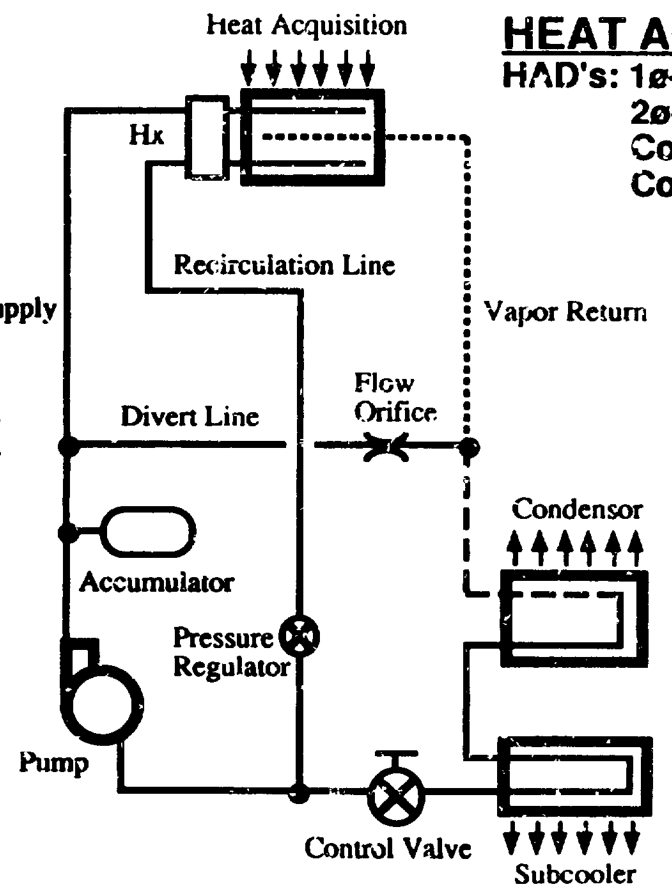


PRINCIPAL SCARS

PRINCIPAL SCARS FOR R & D NODE OR TRANSPORTATION NODE ARE SIMILAR



CTCS FLOW SCHEMATIC AND SUBSYSTEMS



HEAT ACQUISITION

HAD's: 1ø-H2O/2ø-NH3 HX
2ø-NH3/2ø-NH3 HX
ColdPlates
Coldrails

THERMAL TRANSPORT

Transport Lines
Valves, QD's
Pallet Equipment

HEAT REJECTION

Radiator Panels
Condensers
Subcoolers
Rotary Fluid Coupler

HEAT ACQUISITION GROWTH

RESOURCE	AC UNITS	AC HX/CP	R & D UNITS	R & D HX/CP	TRANS UNITS	TRANS HX/CP
MODULES	2 US, 2 I	12	6 US, 2 I	28	4 US, 2 I	20
RESOURCE NODES	4	8	8	16	8	16
POCKET LABS	-	-	3	6	1	2
ATTACHED PAYLOADS	-	-	18	36	8	16
CSF	-	-	1	3	1	3
LTV + MTV FACILITY	-	-	-	-	1	4
DDCU COLDPLATES	20	20	52	52	40	40
TOTAL HX(1)	40		141		101	
TOTAL WEIGHT (LBS)	4660		15570		10890	

PROVISIONS FOR GROWTH

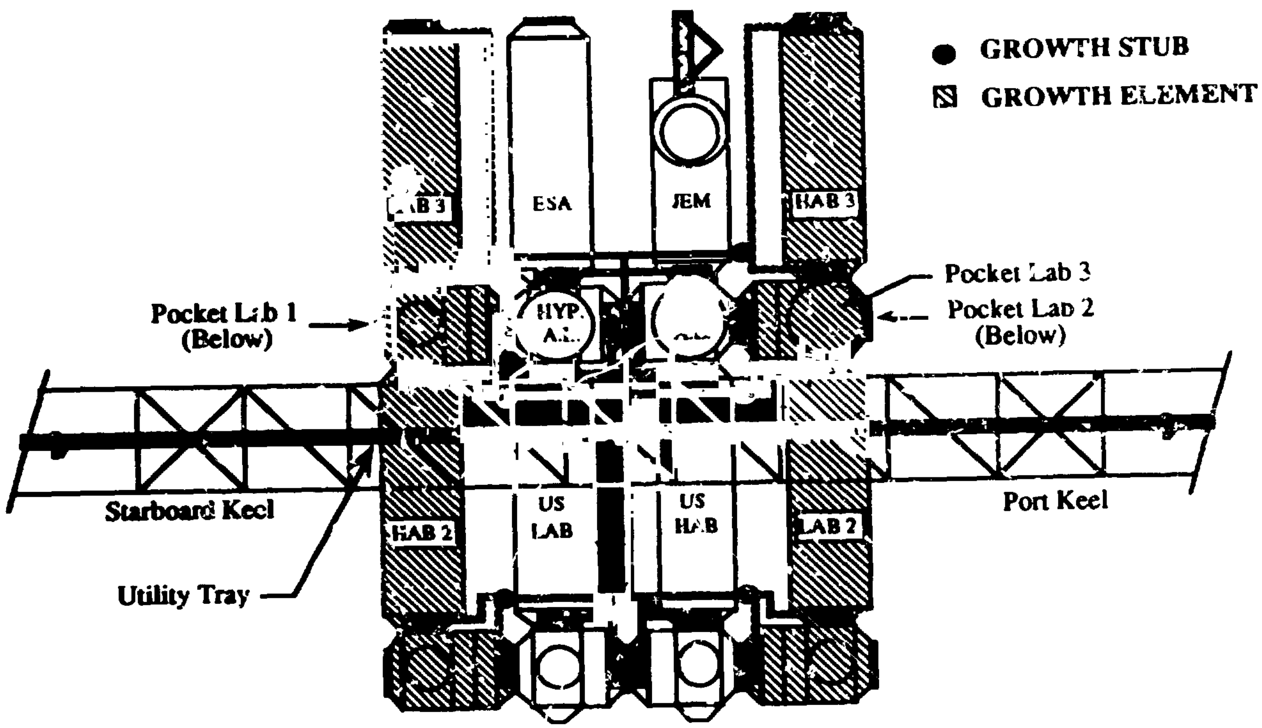
- MODULE, POCKET LAB, AND NODE HEAT EXCHANGERS INTERFACE WITH SECONDARY FEED (FORE & AFT) BRANCHING FROM TRANSVERSE BOOM. THE SECONDARY FEED BRANCH WILL REQUIRE STUBS FOR GROWTH.
- VARIABLE FLOW ORIFICES WILL BE REQUIRED FOR CAPILLARY HAD'S TO ACCOMMODATE ADJUSTMENTS IN SYSTEM PRESSURE AND FLOW RATES ASSOCIATED WITH PHASED GROWTH.

(1) EACH HEAT EXCHANGER UNIT HAS SIX INLET/OUTLET PORTS FOR FLUID CONNECTIONS WITH THE PRIMARY AND REDUNDANT THERMAL LOOPS

Lockheed Engineering & Sciences Company	SSF EVOLUTION TECHNOLOGY WORKSHOP	NASA/JSC - CREW AND THERMAL	
		BY: ERIC OLSSON	DATE: JAN/90

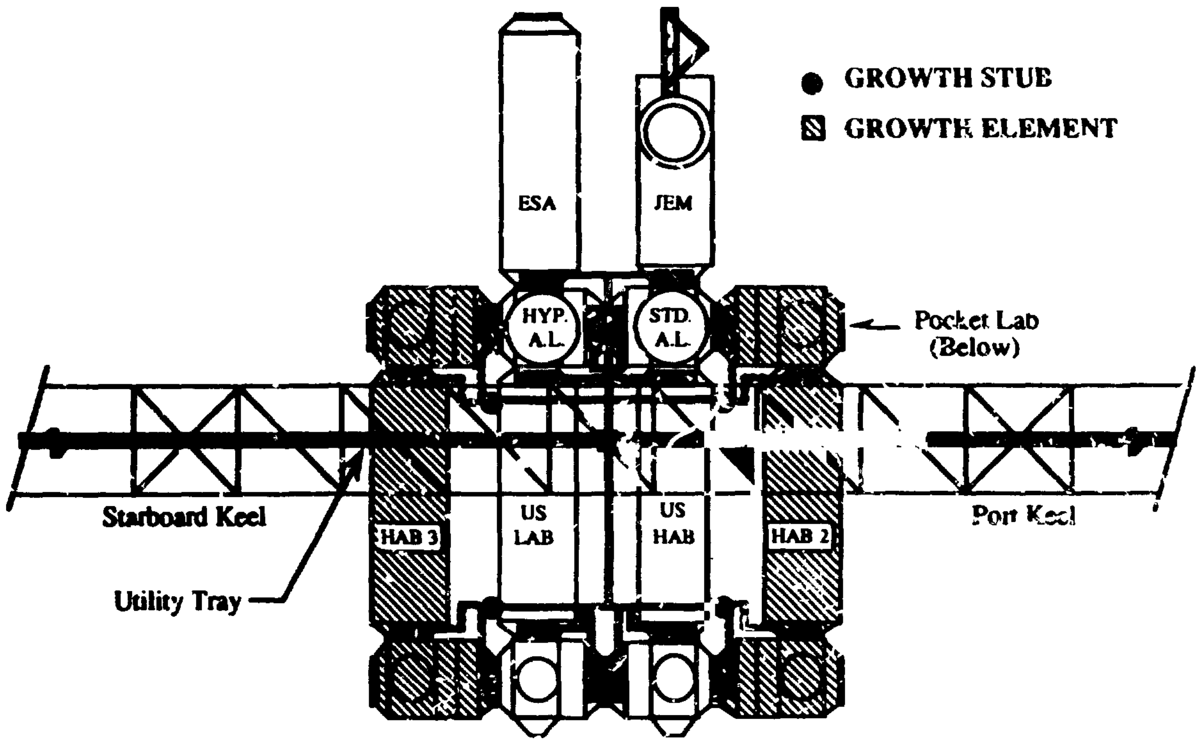
R & D MODULE ATCS FLUID DISTRIBUTION (PRELIMINARY)

MODULE GROWTH IS IN THE ±Y DIRECTION. GROWTH STUBS ARE TO BE PROVIDED ON THE SECONDARY ATCS FLUID DISTRIBUTION BRANCH.



TRANSPORTATION MODULE ATCS FLUID DISTRIBUTION (PRELIMINARY)

MODULE GROWTH IS IN THE ±Y DIRECTION. GROWTH STUBS ARE TO BE PROVIDED ON THE SECONDARY ATCS FLUID DISTRIBUTION BRANCH.



UTILITY DISTRIBUTION SYSTEM GROWTH

ITEM	AC	R&D	TRAN.
LINE LENGTH (FT)	7000	13415	13605
VALVES/QD'S	390	1005	895
TOTAL WEIGHT (LBM)	1610	11170	9660

PROVISIONS FOR GROWTH

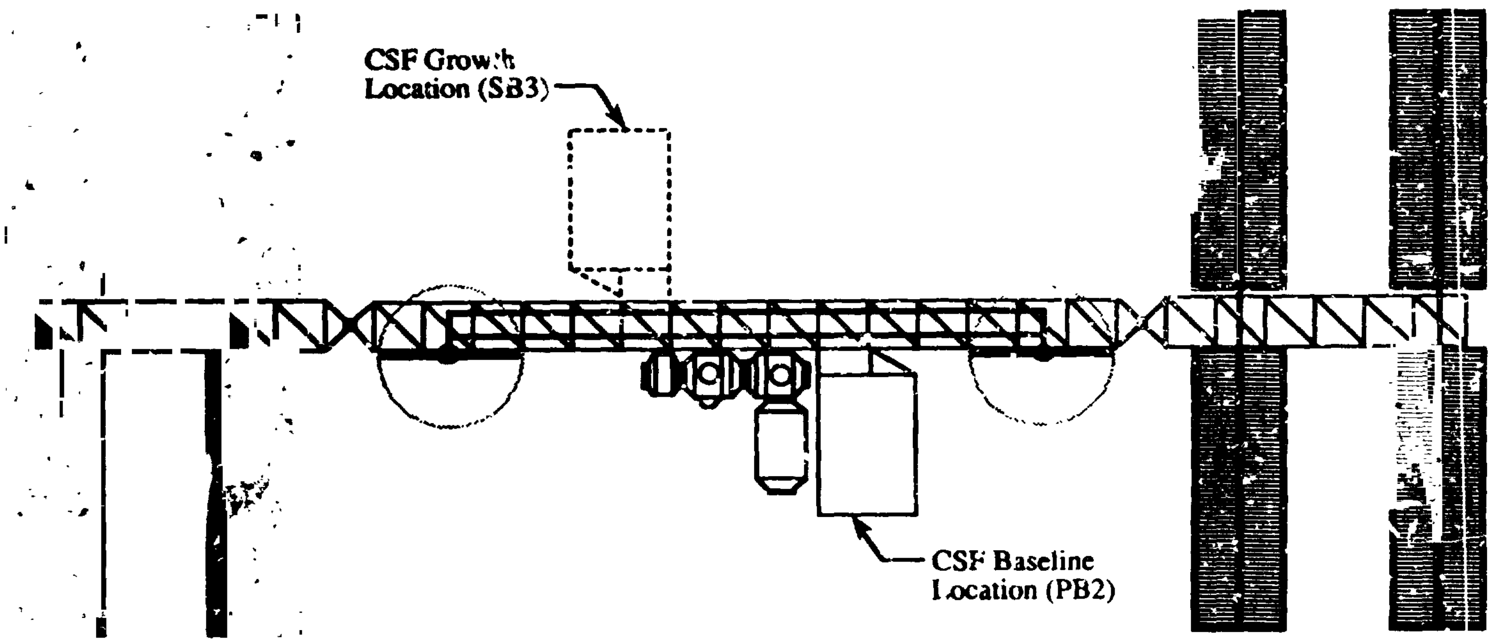
- LINES, VALVES, AND QD'S ARE SIZED FOR GROWTH
- DEPLOYABLE "POP-UP" UTILITY PORTS REQUIRED FOR DUAL KEEL (PB4,SB5) AND CUSTOMER SERVICE FACILITY (SB3)

DESIGN ISSUES

- TCS GROWTH REQUIREMENTS FOR DMS, GN&C, C&T, AND EVA HAVE YET TO BE SPECIFIED.
- PTCS IS BASELINED FOR ATTACHED PAYLOADS AND PALLETS. PASSIVE HEAT REJECTION HAS RESTRICTED VIEWING REQUIREMENTS THAT MAY BE DIFFICULT TO PRESERVE WITH GROWTH. UTILITY PORTS WILL BE REQUIRED IF ACTIVE COOLING IS REQUIRED IN THE FUTURE.
- THERMAL REQUIREMENTS FOR DUAL KEEL ARE NEEDED FOR TCS GROWTH PLANNING.
- CSF GROWTH LOCATION NEEDS TO BE BASELINED

CUSTOMER SERVICE FACILITY

- A UTILITY PORT FOR THE CSF SHOULD BE PROVIDED AT SB3. THE CSF WILL BE RELOCATED OR REBASELINED TO ACCOMMODATE MODULE EXPANSION (ATCS REQUIREMENTS = 25 kw)
- PRESENCE OF CSF CAUSES 1% (β=0) to 5% (β=52) REDUCTION IN HEAT REJECTION RATE



TCS PALLET GROWTH

QUANTITY DOESN'T CHANGE - ONLY SIZE

PROVISIONS FOR GROWTH

- FLUID HANDLING (ORU) EQUIPMENT IS INITIALLY SIZED FOR ___ kW. UPGRADING EQUIPMENT TO LARGER CAPACITY EQUIPMENT MAY REQUIRE INCREASED VOLUME ALLOCATION
  - PUMPS (8)
  - ACCUMULATORS (2)
  - FILTERS (8)
  - NCG TRAPS (4)
- LARGER FILL AND DRAIN TANKS WILL TO ACCOMMODATE ADDED AMMONIA INVENTORY WITH ADDITION OF DUAL KEEL (INCREASES FROM 1600 LBM TO 3200 LBM)
- VOLUME ALLOCATION FOR ADDED FORWARD ROTARY FLUID COUPLERS REQUIRED ON EACH PALLET
- TCS FLUID CONNECTIONS REQUIRED IN EACH LOOP FOR ADDED ROTARY FLUID COUPLERS

HEAT REJECTION GROWTH

ITEM	AC	R & D *	TRAN *
RADIATOR WINGS	2	4	4
HEAT REJECTION SYSTEM			
Radiator Panels	74	280	172
Condenser Panels	14	48	32
SUBCOOLING SYSTEM			
Radiator Panels	8	16	16
Subcooling Modules	4	4	4
SWEEP RADIUS (FT) **	26	46	29
TOTAL WEIGHT (LBM)	12075	39835	26400

* ASSUMES 5% SAFETY FACTOR, AND 36% @ 2°C AND 64% @ 21°C
** ASSUMES 3 INCH PANEL SPACING

PROVISIONS FOR GROWTH

- CONDENSERS ARE MODULAR AT FIXED (6 PANEL) EXPANSION INCREMENTS
- CTB CONDENSER SUPPORT STRUCTURE MUST BE MODULAR OR INSTALLED AT ASSEMBLY COMPLETE FOR FULL COMPLEMENT OF RADIATORS
- SWEEP VOLUME FOR THERMAL RADIATOR WINGS FORE AND AFT OF TCS PALLETS MUST BE PRESERVED

HEAT REJECTION GROWTH ... Con't

DESIGN ISSUES

- PANEL-TO-PANEL RADIATOR SPACING AFFECTS RADIATOR TOTAL SWEEP DIMENSION. FOR R & D NODE, WITH 1 INCH PANEL SPACING ONLY 2.6 FT CLEARANCE IS AVAILABLE BETWEEN CTCS AND EPS THERMAL RADIATORS. THE REQUIRED EVA CLEARANCE IS 7 FT .
- HEAT LOAD SPLIT BETWEEN 2°C AND 21°C THERMAL LOOPS AFFECTS TOTAL NUMBER OF PANELS (36% LOAD ON 2°C BUS, 64% LOAD ON 21°C BUS). THIS LOAD FRACTION IS SUBJECT TO CHANGE.
- PRESENCE OF CSF REDUCES RADIATOR HEAT REJECTION BY 1% (β=0) to 5% (β=52).

MONITORING & CONTROL GROWTH

MAJOR FACTORS

- TCS PHYSICAL EVOLUTION - ADDED ORU'S, DISTRIBUTION LINES
- TECHNOLOGY EVOLUTION = "EXPERT SYSTEMS"
  - TASK ORIENTED COMMANDS ⟶ GOAL DRIVEN COMMANDS
  - FDIR ⟶ FAULT PREDICTION, TREND ANALYSIS

PROVISIONS FOR GROWTH

- TIER III - EXTERNAL SCARS
  - ADDED SENSORS (T, P, ΔP, Q) INCREASE FROM 675 TO 1050. EXPERT SYSTEM TECHNOLOGY WILL INCREASE THIS FURTHER.
  - VOLUME ALLOCATION FOR MDM'S. TOTAL NUMBER OF SIGNALS INCREASE FROM 4200 TO 12000. THIS TRANSLATES TO 120 ADDED MINI-MDM'S (64 PORTS EA).
  - LOCAL BUS INTERFACE PORTS FOR ADDED MDM'S
- TIER II - INTERNAL HOOKS
  - (SDP) SOFTWARE UPGRADES
  - (RODB) INCREASED MEMORY ALLOCATION
  - (LOCAL BUS) INCREASED COMMUNICATION CAPACITY REQUIREMENTS
- TIER I - INTERNAL HOOKS
  - SOFTWARE ENHANCEMENTS

TCS MONITORING AND CONTROL HIERARCHY

TIER I - STATION OPERATION

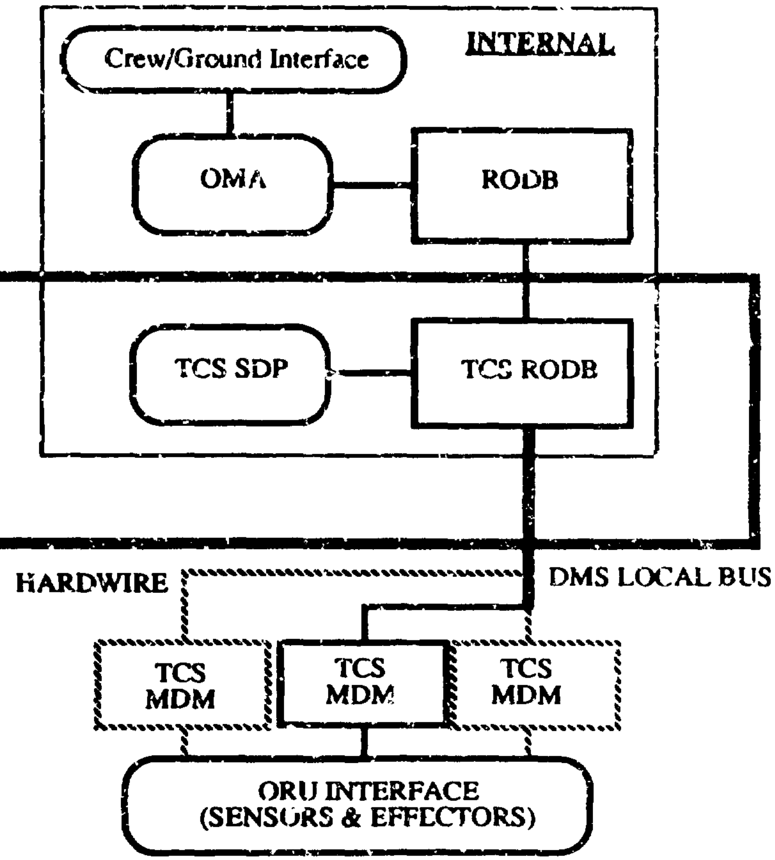
- Subsystem Directives, Health, and Status

TIER II - SUBSYSTEM OPERATION

- TCS Software Procedures
- Component Status and Performance Data
- Fault Detection, Identification, and Recovery (FDIR)
- External Local Bus Interface

TIER III - ORU OPERATION

- Data Acquisition and Signal Conditioning
- External Hardwire Interface



TECHNOLOGY GROWTH

- **ACADEMIC ISSUES**
  - TWO-PHASE FLOW TECHNOLOGY
  - THERMO-OPTICAL COATING MATERIALS

- **COMPONENT LEVEL ISSUES - GROWTH THROUGH MODULARITY**
  - BIGGEST IMPACT: HEAT PIPE RADIATORS
    - GOVERNS TOTAL HEAT REJECTION CAPABILITY
    - LARGEST WEIGHT COMPONENT IN CTCS ~ 65%
    - LARGE SWEEP VOLUME ALLOCATION

- **SYSTEM LEVEL ISSUES - INTEGRATION ISSUES = HOOKS AND SCARS**
  - ADVANCED HEAT PIPES - ARTERIAL FLOW, COMPOSITES, ETC
  - HEAT PUMP CYCLE - HIGHER TEMPERATURE FOR HEAT REJECTION PURPOSES
  - CONDENSERS - INTEGRAL CONCEPTS
  - INSTRUMENTATION - TWO-PHASE VOID FRACTION, LEAK DETECTION
  - MONITORING AND CONTROLS - EXPERT SYSTEMS

CONCLUSIONS

- INITIAL SCAR ASSESSMENT FOR "R & D NODE" AND TRANSPORTATION NODE IS COMPLETE. THE PRINCIPAL SCARS FOR EACH CONFIGURATION HAVE BEEN IDENTIFIED. THE SCARS PERTAIN TO:
  - (1) FLUID CONNECTIONS FOR MODULES, PAYLOADS, DUAL KEEL, SERVICING FACILITIES, AND RFC.
  - (2) VOLUME ALLOCATION FOR THERMAL RADIATORS AND MDM'S.
- CLEARANCE BETWEEN CTCS AND EPS THERMAL RADIATORS FOR THE R & D NODE IS A POTENTIAL PROBLEM, WHICH S LINKED TO THE MINIMUM PANEL-TO-PANEL RADIATOR SPACING. FOR THE TRANSPORTATION NODE, PHYSICAL AND EVA CLEARANCE IS PROVIDED.
- THE CTCS COMPONENT THAT HAS THE IMPACT ON GROWTH IS THE THERMAL RADIATOR (VOLUME ALLOCATION, WEIGHT, AND PERFORMANCE)
- SOFTWARE AND AUTOMATION APPLICATION DEVELOPMENT IS STILL AT "INFANCY STAGE". THIS INSTILLS A LEVEL OF UNCERTAINITY WITH REGARD TO GROWTH REQUIREMENTS. FOR EXPERT SYSTEMS THE NEED FOR ADDITIONAL SENSORS, MDM'S, AND DEDICATED TCS PROCESSORS IS EXPECTED.
- TRUSS MOUNTED EQUIPMENT (APAE'S, PALLETS) USING PTCS SHOULD INCLUDE BLOCKAGE EFFECTS DUE TO GROWTH, OR ACCOMMODATION FOR FUTURE CONNECTION TO THE CTCS SHOULD BE PROVIDED.
- A STRONG EMPHASIS HAS BEEN PLACED ON MODULARITY IN BASELINE REQUIREMENTS WHICH HAS PROVIDED FLEXIBILITY TO ACCOMMODATE GROWTH

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THERMAL EXPERT SYSTEM - TEXSYS

ADVANCED AUTOMATION OF A PROTOTYPIC THERMAL CONTROL SYSTEM FOR SPACE STATION

PRESENTED BY CHIN LIN

CREATED BY JEFF DOMINICK

The Thermal Expert System (TEXSYS) was initiated in 1986 as a cooperative project between ARC and JSC as a way to leverage on-going work at both centers. JSC contributed Thermal Control System (TCS) hardware and control software, TCS operational expertise, and integration expertise. ARC contributed expert system and display expertise. The first years of the project were dedicated to parallel development of expert system tools, displays, interface software and TCS technology and procedures by a total of four organizations (two at ARC, two at JSC). A demonstration was planned as the final project milestone.

BACKGROUND

JSC DEVELOPING STATION THERMAL CONTROL SYSTEM

- New two-phase (liquid/vapor) technology
- Operational expertise

ARC CONDUCTING SYSTEMS AUTONOMY DEMONSTRATION PROGRAM

- Development of expert system and display tools
- Goal of real-time control and FDIR of a system

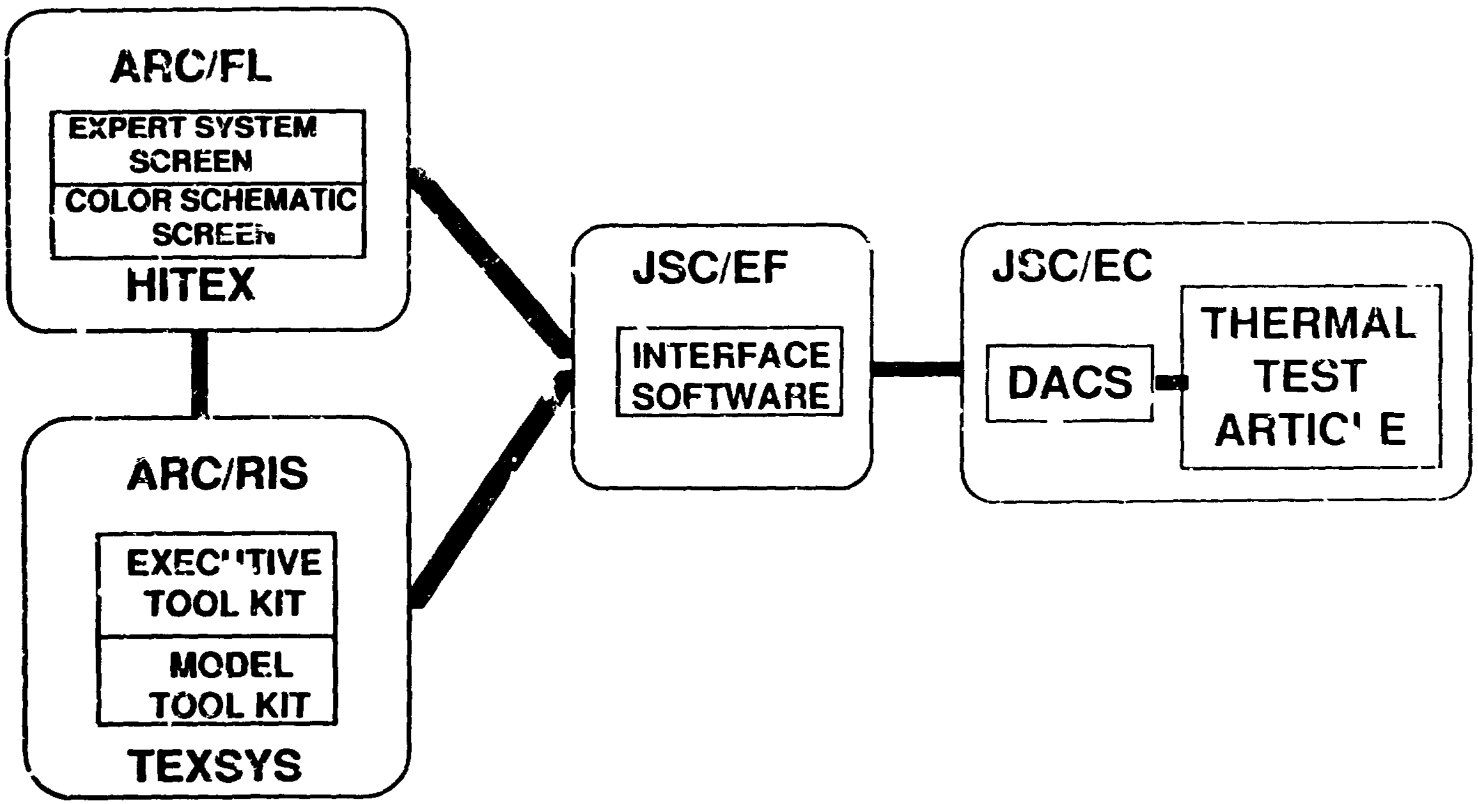
COOPERATIVE PROJECT

THERMAL EXPERT SYSTEM SELECTED 1986

- Parallel development of expert system tools, thermal technology, interface software
- Combined effort of two ARC (FL & RIS) and two JSC (EC & EF) organizations
- Demonstration planned as final milestone

TEXSYS consisted of four major software units layered on top of one another. JSC developed both the conventional control software that interacts with the test article and its interface software to the expert system. ARC developed the Thermal Expert System (TEXSYS) and the human interface to TEXSYS (HITEX). TEXSYS and HITEX each ran on a dedicated Symbolics computer, while the conventional control software ran on two microVax computers. All the computers were networked to one another, with the interface software distributed between all the computers.

OVERVIEW OF TEXSYS



TEXSYS is one of the first real time expert systems to perform control on a large, complex physical system. It was actually developed in an iterative fashion, with its first step to interact with a smaller TCS brassboard test article. The system was then upgraded to handle the actual test article and more faults, and was progressively tested and corrected to its final demonstration configuration. It uses model-based reasoning (327 rules and 3,493 frames) and its networking of software interfaces must fit into a 15 second cycle time.

SYSTEMS AUTONOMY DEMONSTRATION PROJECT

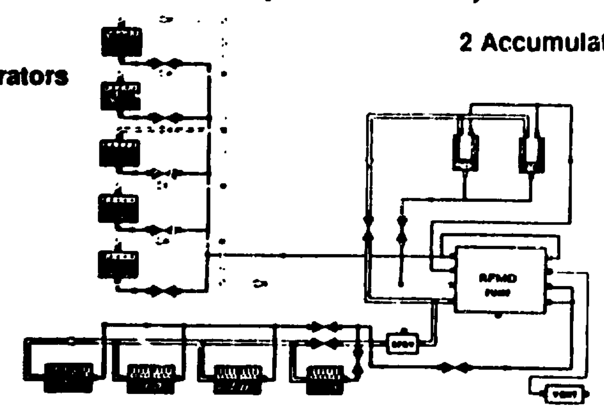
ADVANCED AUTOMATION DEMONSTRATION OF SPACE STATION FREEDOM THERMAL CONTROL SYSTEM

TECHNOLOGY CHALLENGE

EXPERT SYSTEM REALTIME CONTROL OF A COMPLEX ELECTRO-MECHANICAL SYSTEM

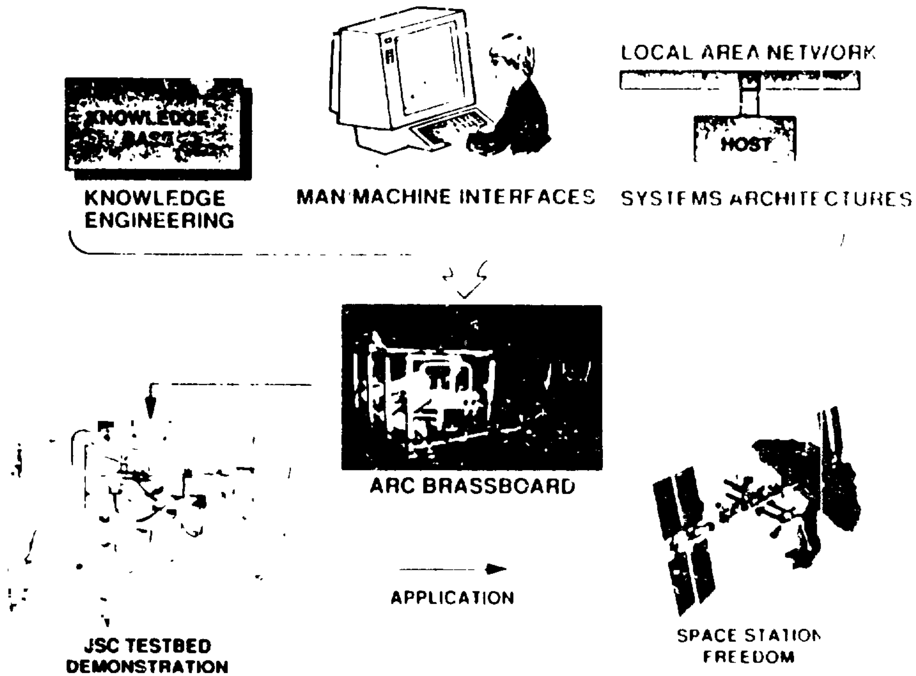
- ***Advanced Thermal Technology***
- ***Complex Physical System***

THERMAL CONTROL SYSTEM (TCS)
Two-Phase Anhydrous Ammonia System



TECHNOLOGY IMPLEMENTATION

JOINT ARC/JSC DEMONSTRATION



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TEXSYS was designed to conduct both real time control and fault detection, isolation and recovery (FDIR) of the thermal test article. From a list of 38 potential faults, ten faults were selected for implementation and demonstration in TEXSYS The test article was configured to allow detection of all 10 faults with varying levels of automatic recovery.

SPECIFIC FUNCTIONALITY TO BE DEMONSTRATED

REAL-TIME CONTROL

STARTUP

NORMAL OPERATIONS

SHUTDOWN

FAULT DETECTION, ISOLATION, AND RECOVERY OF 10 COMPONENT LEVEL FAULTS

1. Slow Leak
2. Pump Motor Failure
3. Single Evaporator Blockage
4. High Coolant Sink Temperature
5. Temp Valve Failure
6. NCG Buildup
7. Temp Valve Actuator Failure
8. Excessive Heat Load on Single Evaporator
9. Accumulator Position Sensor Failure
10. Pressure Sensor Failure

The TEXSYS project culminated with 5 months of integration and checkout, followed by a one week demonstration. TEXSYS successfully conducted all of its control and FDIR procedures. It proved to be generally reliable for conducting fault detection. Both the fault detection capability and the graphical displays were significant improvements over the conventional controller. Slowdowns in processing time decreased the reliability of the expert system. Future upgrades to the system should address the slowdowns and improve the fault detection explanation capability.

RESULTS

SOFTWARE INTEGRATION/CHECKOUT PERFORMED AT JSC MARCH - AUGUST 1989

- Simple interface tests approx 3 weeks
- Playback of pre-recorded test article data approx 3 months
- Actual interaction with live test article approx 6 weeks

DEMONSTRATION WEEK (8/28 - 9/1/89) SUCCESSFULLY SHOWED ALL NORMAL OPERATING PROCEDURES AND FAULT DETECTION ON ALL 10 FAULTS

STRENGTHS

- Significant improvement over previous capability
- Excellent graphical displays
- Generally reliable Fault Detection capability

WEAKNESSES

- Slowdowns in processing time decreased reliability, ease of use
- On-screen explainations need to be enhanced

Advanced automation technology provides useful tools to engineers attempting to capture and utilize design and operational expertise. TCS engineers can use this technology to better design thermal systems for future programs.

One of the biggest difficulties has been, and continues to be in the ability to design a system and in parallel design and codify its operational procedures. Advanced automation tools are beginning to add extra flexibility over conventional tools to better allow the capture of design and operational expertise as a system develops. Further research is required to find effective tools to checkout and certify this type of software.

The presentation concludes with self-descriptive two page list of Lessons Learned that were gained during the TEXSYS development and test.

CONCLUSIONS

1. TCS Engineers better prepared to develop automation software for Space Station, Advanced Programs.

2. Expert System community has more experience with large model-based expert systems for real-time process control.

3. Codifing new hardware operating procedures using new advanced automation techniques is a challenge.

4. Further research is needed into use of simulation software and other tools to develop and checkout expert systems.

LESSONS LEARNED

1. Identify user, focus on his application. Application and knowledge engineers should work together to:
   - Develop requirements early in the project
   - Define the operating and fault diagnosis procedures
   - Conduct a code walkthrough
   - Conduct hardware/software testing

2. New technology adds development time.
   - Application operational immaturity required extra time to develop fault diagnosis and recovery procedures
   - Real-time model-based expert system tools required development and checkout time

3. Iterative coding and testing is an effective expert system development process.
   - Brassboard testing stressed performance
   - Playback of pre-recorded test article data improved accuracy
   - Full-up testing is a final step

LESSONS LEARNED

4. Slow system, dedicated computers ease real-time performance problems.
   - TCS parameters, in general, change slowly with time (~seconds)
   - TEXSYS project employed two Symbolics computers (TEXSYS and HITEX) and two microVax computers (Conventional control and Interface software)
   - Network and microVaxes were tuned to optimize performance

5. Clean interfaces eased integration between conventional and expert system code.
   - ICD
   - Modular subroutines in conventional software

* U.S. GOVERNMENT PRINTING OFFICE: 1990--730-163/E4549

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